ELECTRICITY

ITS HISTORY AND DEVELOPMENT

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BY

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WITH ILLUSTRATIONS

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To My Wife

LAURA KELLOGG WEAVER DURGIN

FOREWORD

THIS book is intended for the man who desires a fair understanding of present-day electricity, but who finds the statements of the text-books and manuals more detailed than he needs and a bit too dry to hold his interest. By considering the main events in the development of electrical applications it seemed possible to preserve some of the romance of the work of the pioneers, past and present, and at the same time to give clear conceptions of the fundamentals. This has been attempted in the following pages; and if the work serves to lighten the mystery of electricity for a few, or to show the charm and adventure which still await those who choose electrical work as their vocation, it will, perhaps, have justified publication.

W. A. D.

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I

The Occasional Discoveries of Twenty-three Centuries

ELECTRICITY! What is it? Who discovered it? What ideas are hidden in this jargon of "volts," "amperes," and "kilowatts," which the electrical man uses in his kind efforts to make all clear? Surely there must be some simple way of representing the energy which now supplies our best light, our best power, and our best transportation. The fundamentals are but the result of slow elementary evolution; and by reviewing the main steps of this evolution we should find it easy to get a few conceptions which will make the electric generator as familiar as the steam boiler, the electric motor as the steam engine, the tungsten lamp as the gas flame; which, in short, will make commonplace of the mystery.

585 B. C. is usually taken as the birthdate of

electricity, for it represents the period of Thales, who is reported by Aristotle to have said, "The stone has a soul since it moves iron."

Something over twenty-five hundred years ago, then, it had been discovered that certain pieces of a particular iron ore, the variety now called magnetite, possessed the power of attracting other similar pieces and of moving small articles of iron, and it was this commonly known phenomenon which Thales first recorded in his fantastic theory. The best specimens of these stones were obtained in the City of Magnesia and before many centuries the name "magnets" was coined. The first word of our technical vocabulary and Thales' scientific fame are thus both connected with *magnetism*, the science of the properties of magnets; and although we shall find these magnetic actions to be very closely intermingled with most present applications of electricity, we must admit that such efforts are not strictly electric. This latter term is reserved for phenoména growing out of another observation of the ancients; that when the mineralized resin, *amber*, was rubbed, it exhibited an attraction for light materials; but as this effect was early classed with that of the magnet it has been assumed, with somewhat weak logic, that Thales knew of it, and that he may be fully accredited, therefore, as the earliest electrical discoverer.

The beautiful golden amber, named electron by the Greeks for its suggestion of sunlight, was used for jewelry from the earliest times, and the attractive power of hair ornaments or of the spindles made for the wealthier women's spinning must have been soon noticed. But although the amber attraction was thus probably known long before that of the magnet, no definite description occurs in ancient writings until about 300 B. C., when Theophrastus notes that, "Amber is a stone. It is dug out of the earth in Liguria and has a power of attraction. It is said to attract not only straws and small pieces of sticks, but even copper and iron, if they are beaten into thin pieces." In this quotation and that from Aristotle are presented a complete summary of recorded electrical and magnetic knowledge for over fifteen hundred years, with the single exception that some time before 100 A. D. it had been observed, as Plutarch writes, that "iron drawn by stone often follows it, but often also is turned and driven away in the opposite direction."

About the middle of the twelfth century, a practical use for the magnet's properties was found, in the compass. This device, first described in 1180 by Alexander Neckham, an English monk, is often credited to the Chinese, but was probably invented by sailors of Northern Europe. It implies

a knowledge of the facts that (a) when a natural magnet — or, as it now came to be called, a "lodestone" or "leading stone" — is suspended and free to turn about a vertical axis it will always take a position such that the same definite portion is toward the north, and (b) that by rubbing a piece of iron with the lodestone the attractive and directive properties of the stone may be temporarily imparted to the iron.

The first compasses consisted of needles of iron thrust through pieces of wood and floated in vessels of water. The needles were only used in cases when the pole star could not be seen, and had to be rubbed with the lodestone or *magnetized* each time. A very crude instrument, this, but quite sufficient to lead to the discovery of a new continent, quite sufficient to put the magnet and amber attractions first among the phenomena interesting Roger Bacon and his contemporaries. Small discoveries were made by many philosophers, and when in Elizabeth's reign her physician, Dr. William Gilbert, took up the subject as an avocation for his leisure, he found a considerable accumulation of data, true and false, as a basis for the researches which have gained him the name of the father of electricity. The ends of the suspended magnet pointing to the north and south were already named *the poles*, and it had been found that the north pole

of one magnet attracted the south pole of another, a fact which Gilbert verified, although he misinterpreted the equally true relation that two south poles or two north poles repel each other.

It had been observed, too, that the magnetic force was manifested at a considerable distance from the lodestone. Robert Norman had conceived the idea that the magnet was surrounded by a "sphere of vertue," and wrote: "I am of the opinion that if this vertue could by anie means be made visible to the eie of man, it would be found in sphericall forme, extending round about the stone in great compasse and the dead bodie of the stone in the middle thereof." As in most cases, Gilbert improved this theory, imagining the sphere, or, as he called it, "orb of vertue," extending to remotest space, the magnetic force being exercised along lines which he called rays of magnetic force. Today instead of the "orb of vertue" we speak of the *field of force* surrounding a magnetic pole; and Gilbert's "rays" are now called *lines of force,* but, as will be noted later in reviewing Faraday's discoveries, the present ideas of the space surrounding a magnetic pole are very similar to Gilbert's theory. Norman's discovery in 1576 that in England a needle suspended to turn freely about a horizontal axis pointed down toward the north, or *dipped,* cleared another path for Gilbert, for it was soon found that the dip varied with

location, being 0° at the equator and increasing toward the poles.

From this dipping and the attraction of unlike poles Gilbert evolved the theory that the earth itself was a magnet, testing his conclusions by constructing a small globe of lodestone toward which small needles behaved in exactly the way that the compass and dipping needle acted toward the earth. He saw at once that the magnetic pole of the earth at the north geographical pole would be called north, and hence the pole of the compass pointing north ought to be called south and not north, as was and is the universal custom. This has always led to confusion which can be avoided only by taking the compass needle as the standard, and agreeing that the magnetic pole of the earth which lies near Peary's goal is south.

Experimenting with a dipping needle on his lodestone globe, and observing that the dip was 0° at the equator and increased gradually toward the poles, until at these two points the needle became vertical or dipped 90°, Gilbert came to the conclusion that a dipping needle could be used to determine latitude. Here, unfortunately, he went astray, for although the dipping needle is horizontal near the equator and does become vertical at the magnetic poles of the earth, these poles do not coincide with the geographical poles, and the

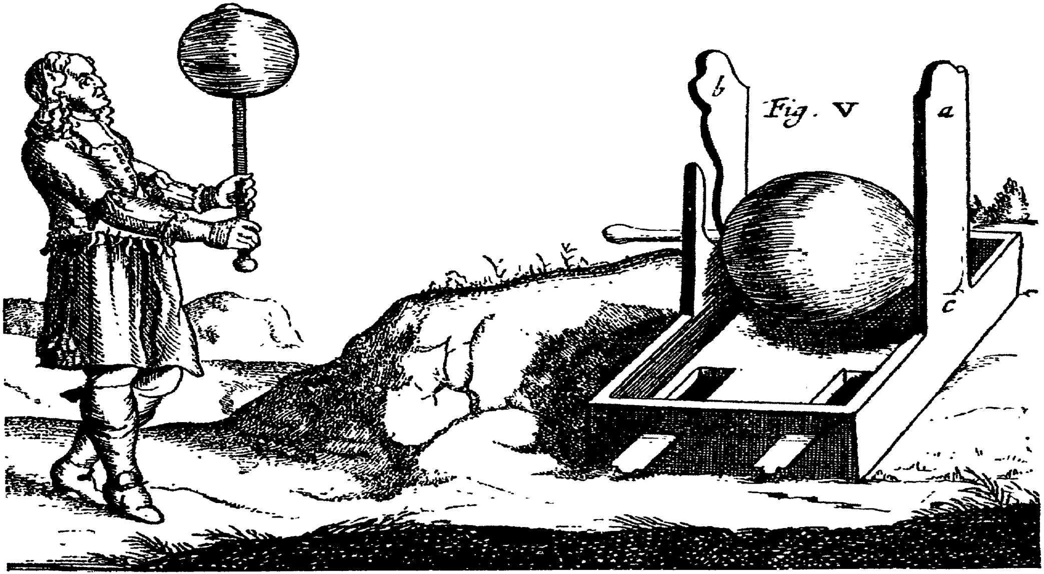
unequal distribution of the earth's magnetism leads to wide deviations from the uniform variation of dip which Gilbert assumed. The error was soon discovered in the attempt to use the dipping needle in navigation, and engendered so much hostile criticism as to retard the acceptance of the truth of the earth's magnetism.

Beside this greatest of magnetic discoveries Gilbert also found that the attraction of a magnet for iron can not be cut off by interposing any substance except an iron plate; that the attracted iron or steel body is magnetized before it touches the magnet — or, as we now say, *magnetized by induction* — having a polarity opposite to that of the magnet, so that a north magnet pole *induces* a south pole in the approaching iron and these unlike poles attract; that the magnetic force moves from one end of an iron rod to the other, so that magnetic attraction is manifested at the distant end of a rod in contact with a magnet; and that although the magnetic action is strong only at the poles, the force permeates every part of the mass, for when the stone or steel is broken into particles, no matter how small, each proves to be a magnet with new poles. It is doubtful, however, whether he observed that when one polarity is induced at the near end of a rod, the opposite polarity appears at the far end, or that the induced poles, though never attaining

the strength of the inducing magnet, grow stronger as the iron approaches it.

Turning from his work with the lodestone, Gilbert began a series of careful experiments upon the amber attractions. He was rewarded with the discovery that not only amber, but a large class of other substances, manifest the property. From this discovery dates the recognition of electricity as a separate science, for Gilbert demonstrated at once that there was nothing in common between this attraction for any light object which brisk rubbing excited in more than half of the substances he tried, and the natural attraction of the lodestone for iron only. The amber attraction was evidently a much more general property, and for those bodies which possess it he invented the name "electrica," or *electrics*, thus supplying the root for the word which soon came into use, electricity.

The quickening scientific interest of Europe found in the new "electrics" a broad field for experiment. Some time about 1650 Otto von Guericke, burgomaster of Magdeburg, bethought him that a machine might be constructed to do the brisk rubbing with less labor. He built a ball of sulphur on a shaft which could be readily twirled while the palm of the hand was applied as the rubber on the surface of the globe. With this apparatus for a source of electricity he discovered that just as



von Guericke's electrical machine and sulphur globe

magnetism passes from one end of an iron rod to the other, so the electric attraction passes along a linen thread placed in contact with the globe and appears at the distant end; that is, the thread *conducts* the electricity, or is a *conductor*. A very poor conductor it is, transmitting an attraction hardly sufficient to deflect the thread toward an approaching finger; but here, in the burgomaster's workroom, is born the *electrical transmission of energy*. Some fifty years later Francis Hawksbee substituted a glass globe for the ball of sulphur and belted the shaft to a large wheel with crank attached, so that high speeds of revolution could be obtained. When this glass globe was exhausted of air and rubbed, a beautiful glow light filled the sphere, and the English Royal Society meetings became agitated with discussions of the "new electric light."

But the attention of the society was soon taken by the discoveries of Stephen Gray, who succeeded in conducting the electric attraction nearly 1,000 feet over threads of hemp, supported on silk threads. He found, however, that the experiment failed when he used metal wires for a support; and thus he was led to further experiments, which showed that while linen, hemp, or metal would conduct electricity, silk would not. Evidently, then, the metal supports conducted the electricity away

from the hemp thread before it reached the distant end, while the silk supports offered no *conducting* path. Chas. du Fay, a Frenchman, repeating Gray's experiments in 1733, speaks of the hemp threads as being *insulated*, when supported by silk. From this we have our present use of the term *insulator*, as meaning any substance which conducts electricity so poorly that for practical purposes we may consider such conduction to be zero.

With this conception of an insulator once formulated, Du Fay proceeded to experiments which quickly showed him that Gilbert's "non-electrics" —bodies which failed to become electrified when rubbed—were simply conductors, and that when these conducting bodies were mounted on an insulating base or handle, friction at once produced electrification. In Gilbert's experiments the electrification or *charge* of electricity which the friction had generated on his non-electrics had been conducted away immediately by the experimenter's body, while the charge stayed on the insulators, or electrics, until gradually dissipated by moisture particles in the air. This dissipating effect of moisture follows from another contribution of Du Fay, for, after verifying Von Guericke's observation that a feather was first attracted to an electrified rod and then repelled, he came to the conclusion that the feather was electrified by contact with the rod and

that electrified bodies repel one another. Particles of moisture, thus, are attracted to a charged body, electrified and repelled, each particle carrying away a tiny part of the total quantity of electricity.

No sooner was this theory of the repulsion worked out than Du Fay obtained results which apparently disproved it. The feather or bit of gold leaf, after touching the glass rod, was repelled, to be sure, but it was attracted by a piece of electrified resin! He soon saw, however, that all the effects could be explained on the assumption of two kinds of electricity — one produced by rubbing glass, which therefore he called *vitreous;* the other by rubbing resin, and hence named resinous. Two bodies electrified with the same kind of electricity, then, repelled, but two oppositely electrified bodies attracted each other. This explanation, the two-fluid theory of electricity, as it is called, has long since been discarded as a true statement of physical facts, but it is still of use in affording a simple conception of the phenomena.

All these effects depending upon the influence of rubbed glass rods or revolving globes were necessarily feeble because of the small size of the electric machines. Could not some way be devised of accumulating or storing the electricity — adding the product of the machine little by little until a considerable amount was obtained? Thus thought

Von Kleist, Bishop of Pomerania, in 1745. Glass was known to be a good insulator and water a good conductor, so, partly filling a glass bottle with water and arranging a nail to lead from the machine to the water, he held the bottle in one hand and worked his machine with the other. After some minutes he tried to disconnect the nail and was greatly terrified to "receive a shock which stuns my arms and shoulders." He had succeeded — the electricity had accumulated far beyond his expectations — and the *Leyden jar* was discovered. The discovery was remade independently at the University of Leyden in the same year; whence the name of the jar. Experiments soon showed that the hand outside the glass was just as important as the water within, and hand and water were replaced with tinfoil coatings as in the jars now used. This led at once to the discovery that the outer coating must be connected to the rubber of the machine for the best action; and that the larger the jar the greater was the accumulation.

Here at last was sufficient electricity to produce a real stir in the world. Writing in 1795, Cavallo says:

> In short nothing contributed to make Electricity the subject of the public attention and excite a general curiosity until the capital discovery of the vast accumulation of its power in what is commonly called the Ley-

den phial, which was accidentally made in the year 1745. Then, and not till then, the study of Electricity became general, surprised every beholder, and invited to the houses of electricians a greater number of spectators than were ever assembled together to observe any philosophical experiments whatsoever.

What some of these experiments were and what light was thrown on the nature of this new mysterious energy we must now consider.

II

THE AMERICAN PROMETHEUS

BENJAMIN FRANKLIN, printer, in Mr. Penn's colony in America, turned for amusement, about 1746, to repeating the newly published experiments with rubbed glass tubes and Leyden phials. With true beginner's luck he at once made the discovery that a metal point held near an electrified body discharged the electrification without the passage of sparks. When the experiment was made with a charged cannon ball and a pin in the darkened room, a glow could be seen at the pin point but no sound was heard, and the phenomenon came to be called *silent discharge*. Here at the very beginning of Franklin's electrical work was the embryo lightning rod.

Of all the startling discoveries following close upon that of the Leyden jar none appeared more incredible to the English scientists than that American colonists, amid the urgencies of their assumed vocations of hewing down the forest and the Indians, could find time and ability to make genuine contributions to the knowledge of Electricity. In

consequence, the reality of the silent discharge phenomenon was disputed on every hand, the controversy growing more and more acrimonious until at the time the Revolutionary War broke out, King George himself issued a decree that the points be removed from the newly erected lightning conductors and ball tips substituted. Science must be governed by loyalty and in such a crisis it was evident that all colonial ideas must be wrong. But in the meantime Franklin had secured the respectful attention of the scientific world.

His interest had been excited by reading of the experiments which Dr. Watson had made in discharging a Leyden jar through a wire laid over Westminster bridge. Three observers had been used; one standing on the bank of the Thames and grasping in one hand an iron rod which dipped in the water while he held the jar in the other; a second observer presenting his knuckle to the knob of the jar and retaining the near end of the wire; and the third standing on the farther bank holding the other end of the wire and another iron rod dipping in the river. All three men got a severe shock when the jar discharged, the *circuit*, as Dr. Watson christened the path of the discharge, consisting of the three observers, the two iron rods, the wire, and the river. The doctor soon found that the earth could be used instead of water for the

return path, and thus succeeded in transmitting a shock over a wire to a point two miles distant. The idea of signaling by this means did not occur to him, although his discovery of the *earth return* was an important step toward telegraphy.

Watson was much more interested in explaining the results than in finding a practical application, however, and developed a complex theory of electricity which was little more than published when an account of Franklin's "one fluid" theory was read to the Royal Society. According to Franklin's idea all bodies in the normal state contain a certain definite amount of the "electric fire," or electric fluid, and are in equilibrium. If by any means this amount is increased in a given body, that body becomes charged *positively*, or + ; if on the other hand the normal amount is decreased, the body becomes —, or *negatively* charged. If a body in either condition approaches one in the normal uncharged state, a spark passes, equalizing the distribution of the total amount, this spark becoming more vigorous as the difference in amount becomes greater. Hence it is most violent between a highly electrified positive and a highly charged negative body. This theory is probably no nearer the physical truth than the "two fluid" theory of Du Fay, but it gives the clearest and simplest conception of the observed relations, and so has maintained a

leading popular position ever since Franklin proposed it.

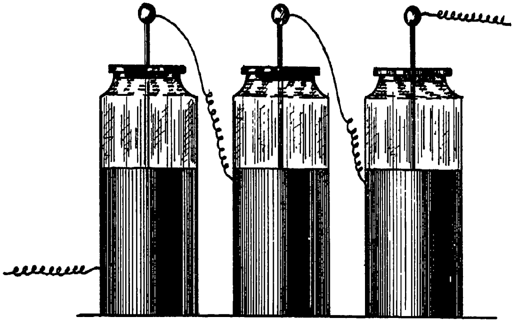
With a mind cleared by his theory, Franklin immediately observed that when charged from a glass-globe electrical machine, the inner coating of the Leyden jar connected to the machine was +, and the outer coating —, and he proceeded to make a form of jar which could be easily taken apart, in order to find just where the electricity was stored. For this purpose he used a pane of glass with sheets of lead on opposite sides, and discovered that the electricity was not in the coatings but was on the surfaces of the glass, held or bound there by the attraction of opposite electrifications until a path was provided by which the + and — charges could reunite. Again the European theory was controverted. All observers had supposed the electricity to be contained in the water, iron filings, or lead plate used to fill the jar, and it took some time for them to accept Franklin's view that these coatings merely served to conduct the charge to the inner surface of the glass, while an equal charge was conducted away from the outer surface by the exterior coating. But truth was with Franklin, and his explanation gradually displaced all others.

Evidently, if the electricity was stored on the surface of the glass, the quantity of the charge which a jar could hold would be increased in pro-

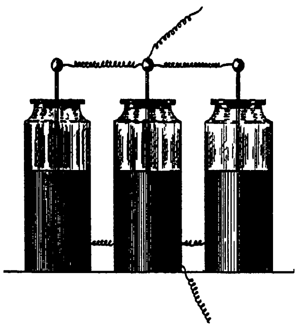
portion to the surface, and two jars with the two outer and two inner coatings connected would hold twice the charge, or have twice the *capacity* of a single jar.

Franklin verified this discovery by experiment and, by increasing the number of jars to six or more, evolved what he called an electric battery which gave a sufficiently powerful discharge to kill a turkey weighing ten pounds. The arrangement of jars so that all the inner coatings were connected together, as were all the outer coatings, making a combination equivalent to a single large jar, he called the *parallel connection;* while he named the connection *cascade* when the outer coating of the first was connected to the inner coating of the second, the outer coating of the second to the inner coating of the third, etc.; so that in charging, as he says, "What is driven out of the tail of the first, serves to charge the second and so on." This arrangement of electrical devices in symmetrical succession giving a single path for the electric flow is now called the *series connection,* but Franklin's term "parallel" is still used for an arrangement which offers simultaneous paths.

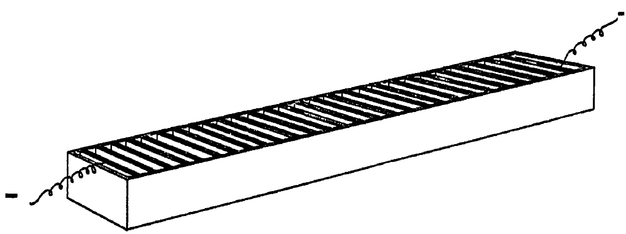
Early in his experiments, Franklin was struck with the similarity between the electric spark and the lightning flash. Others had remarked this, but it remained for the Philadelphia printer to analyze



Leyden jars connected in series



Leyden jars connected in parallel



An early form of trough battery containing twenty-seven "cells" in series [Page 40

the points of similarity and supply the proof of identity. In 1749 he wrote:

> The electric fluid agrees with lightning in these particulars: (1) Giving light; (2) color of the light; (3) crooked direction; (4) swift motion; (5) being conducted by metals; (6) crack or noise in exploding; (7) rending bodies it passes through; (8) destroying animals; (9) melting metals; (10) firing inflammable substances, and (11) sulphurous smell. The electric fluid is attracted by points; we do not know whether this property is in lightning. But since they agree in all the particulars wherein we can already compare them, is it not probable that they agree likewise in this? Let the experiment be made.

A year later he outlined the necessary experiment in a letter to his English friend Collinson.

> On the top of some high tower or steeple, place a kind of sentry box — big enough to contain a man — and an electrical stand'' [a stool with feet made of glass or other insulating material, so that any one standing thereon is insulated from the ground]. ''From the middle of the stand let an iron rod rise and pass, bending out of the door, and then upright 20 or 30 feet, pointed very sharp at the end. If the electrical stand be kept clean and dry, a man standing on it, when such clouds are passing low, might be electrified and afford sparks, the rod drawing fire to him from the cloud.

With the idea of the necessity of a high tower or steeple in mind Franklin cleverly started a subscription to build such a steeple on the Philadelphia meeting house. Contributions were slow, however,

and in the meantime his letters to Collinson were published in England and quickly translated and reprinted in France, where the proposed lightning experiment attracted immediate attention.

In the spring of 1752 three French philosophers, d'Alibard, de Lor, and de Buffon, erected iron rods over their houses or in their gardens, and all succeeded in drawing vigorous sparks from the rods during local thunderstorms. With characteristic enthusiasm the results were immediately communicated to the French Academy and the identity of lightning and electricity proclaimed, due credit being given to Franklin. But when the news reached him he was not satisfied; for none of the French experiments had been made from a high steeple, and the ends of the rods must have been far from the clouds. Unfortunately his own steeple project continued to mature very slowly, and there were no high hills near Philadelphia; but after much pondering upon the necessity of getting nearer the clouds he conceived the famous kite experiment. In his own words:

> Make a small cross of two strips of cedar, the arms so long as to reach to the four corners of a large thin silk handkerchief when extended; tie the corners of the handkerchief to the extremities of the cross, so you have the body of a kite, which being properly accommodated with a tail, loop, and string, will rise in the air, like those made of paper; but this, being of silk, is fitter to bear

the wet and wind of a thundergust without tearing. To the top of the upright stick is to be fixed a very sharp-pointed wire, rising a foot or two above the wood. In the end of the twine, next the hand, is to be held a silk ribbon, and where the silk and cord join a key may be fastened. This kite is to be raised when a thundergust appears to be coming on, and the person who holds the string must stand within a door or window, or under some cover, so that the silk ribbon may not be wet; and care must be taken that the twine does not touch the frame of the door or window. As soon as any of the thunder-clouds come over the kite, the pointed wire will draw the electric fire from them, and the kite with all the twine will be electrified, and the loose filaments of the twine will stand out every way and be attracted by an approaching finger. And when the rain has wetted the kite, so that it can conduct the electric fire freely, you will find it stream out plentifully from the key on the approach of your knuckle. At this key the phial may be charged, and from electric fire thus obtained spirits may be kindled and all the other electric experiments be performed which are usually done by the help of a rubbed glass globe or tube, and thereby the sameness of the electric matter with that of lightning completely demonstrated.

Today theory admits but little difference between this experiment made by Franklin in 1752 and the rod experiments performed by the French philosophers, but to the world of the eighteenth century it appeared much more conclusive.

By continuing the rod to the earth, the "end being three or four feet in moist ground," Franklin produced the lightning rod. He realized clearly the two functions of such a rod: first, discharging

a slowly approaching cloud by equalizing its charge with that of the great earth reservoir through the phenomenon of the silent discharge from points, as in the case of the cannon ball; and second, that of directing and conducting the electric discharge when the approach of the cloud was so rapid or the charge so great that a spark or flash of lightning passed before the silent discharge could equalize the electrical condition. Apparently then, he must have appreciated the great danger of the experiments with rods and kites which soon began to be repeated in different parts of Europe. In either test the conducting path terminated at some distance from the ground, and a direct stroke of lightning must inevitably jump from the terminal to the nearest good conductor, which was most likely to be the body of the observer. This danger was sadly proved by the fate of Prof. Richmann of the University of St. Petersburg, who in 1753 was struck dead by such a lightning bolt from his experimental rod.

For some time Prof. Richmann's death was used as an argument against the lightning conductor, but the difference betwen the well grounded rod offering the best direct path to earth and the incomplete path of the experimental rod was gradually appreciated and Franklin's invention was universally accepted as almost perfect protection against

the dreaded lightning. Modern conditions, the network of wires in and around our cities, the closely set masses of building, and the myriad poles rising to considerable heights, have largely reduced the lightning hazard in the more thickly settled regions; but for isolated buildings the lightning rod installed according to improved methods suggested by Sir Oliver Lodge is still the best protection.

In this proof of the identity of the electric spark and the lightning flash, and in the invention of the lightning conductor, the world gained the first practical results of electrical investigation. A century and a half had passed since Gilbert offered work of equal value in magnetism, but even so the pace of real advance was quickening, and the dawn of the century of electricity was almost at hand. For a decade the friction experiments and kite raisings were repeated, with slight modifications but no improvements of moment; and then, suddenly, with an apparently irrelevant discovery of Galvani, was opened an entirely new field for fundamental pioneering.

III

THE CONVULSED FROG-LEG AND WHAT CAME OF IT

SOMETIME in the latter half of the eighteenth century (the date usually taken is 1786) it chanced that Aloisio Galvani, professor of anatomy in the University of Bologna, was preparing for some electrical experiments in his laboratory while an assistant was completing the dissection of a frog. Numerous sparks, jumping across the terminals of an electrical machine near the frog, produced no unusual result, but suddenly the assistant was astounded by the violent convulsions of one of the dismembered frog's legs which he chanced to be touching with his scalpel just at the instant another spark occurred in the machine. Galvani immediately became interested, had the experiment repeated many times, and finally came to the conclusion that the convulsion was undoubtedly due to electricity. Strange to say, however, he believed that as convulsions could be produced by properly manipulating the scalpel even when no spark discharge took place, the electricity must be generated

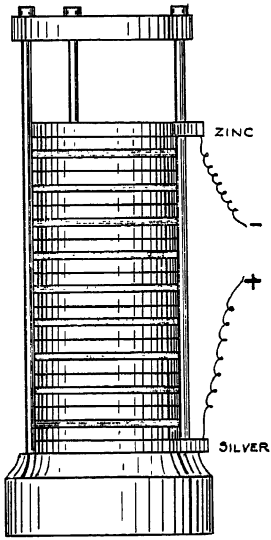
in the frog-leg itself at the internal junctions of nerves and muscles, and was discharged by the contact made through the blade between the exposed muscle and the nerve ends. Indeed, he thought for some time that in this "animal electricity," as he called it, he had discovered the vital force which animates our otherwise lifeless bodies, and his first published description of his experiments presents this theory. Unfortunately for biology today that particular "vital force" still remains to be discovered; but Galvani's work started a series of discoveries resulting in our modern generation of electricity, the vital force of the twentieth century.

Most prominent among the persons attracted by Galvani's papers was his fellow countryman, Alessandro Volta, Professor of Physics at the University of Pavia. Volta had already made an important contribution to electrical science in his invention of the electrophorus, a simple apparatus consisting of a cake of resin to be electrified by friction, and a disc of metal on an insulating handle which could be charged by induction an indefinite number of times from one electrification of the resin cake. The electrophorus was much easier to make than the rotating electrical machines and would operate successfully in damp weather; so it was extensively used for charging Leyden

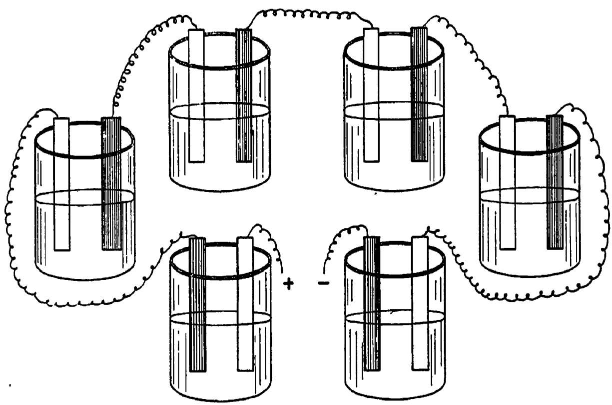
jars and still remains one of the most satisfactory pieces of apparatus easily constructed by the embryo electrical pioneer.

Volta at first accepted Galvani's theory of animal electricity, but after a long series of experiments he found that not only were the convulsions of the frog-leg much more violent when the conductor between nerves and muscles was made up of two wires of different metals twisted together at one pair of ends, the other pair being used for the two contact points, as Galvani had observed, but also the violence of the convulsions depended largely on what particular metals were paired. From the last observation Volta developed his theory that the electricity was generated at the contact of the dissimilar metals and proceeded to develop the remarkable instrument now called the voltaic pile, of which Arago wrote: "Volta's pile, the most wonderful apparatus that has ever come from the hand of man, not excluding even the telescope or the steam engine."

The pile, which was first exhibited in 1800, consisted of a series of discs of silver, zinc, and cloth moistened with salt water, each about an inch in diameter, piled up in a column until the desired number were assembled in regular order, for example, silver, zinc, cloth, silver, zinc, cloth. In Volta's own words this resulted in "the construc-



Volta's pile, the first generator of a continuous electrical current



The "crown of cups" devised by Volta to overcome the evaporation of the electrolyte in his pile

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tion of an apparatus which resembles, so far as its effects are concerned (that is, by the commotion it is capable of making one feel in the arms, etc.), the Leyden batteries, and still more the fully charged electric batteries. It acts, however, without ceasing, and its charge reëstablishes itself after each explosion. It operates, in a word, by an indestructible charge, by a perpetual action or impulse on the electric fluid." Furthermore, the "commotion" was directly proportionate to the number of plates. A single pair produced no apparent effect in the arms, though when the two discs were separated by the tongue and the outer edges touched, a peculiar sour taste was experienced; but one hundred pairs gave a distinct "commotion" and five hundred pairs a very painful one.

The most notable characteristic of the new apparatus was the continuity of the electric discharge in comparison with that from a Leyden jar. Following up the idea of an electric fluid, this continuous discharge was easily conceived as a flow of electricity, or as we say today, a *continuous electric current*. The continuity was soon found, however, to be strictly limited. If the end plates of a pile were connected through a wire, as the moisture in the cloth discs evaporated the current became smaller and finally in a few hours, when the cloth was dry, ceased entirely. To overcome this

difficulty Volta devised his "crown of cups," the cloth discs being replaced with glass cups filled with salt water and the metal discs with strips of silver and zinc.

In Volta's arrangement the silver in one cup was connected to the zinc in the adjacent cup, the silver in this to the zinc in the next, and so on, the series thus beginning with the zinc of the first cup and ending with the silver of the last. From analogy with the Leyden jar battery the arrangement was called the *series connection* of a battery of cups. Attempts were made to secure greater convenience by using a single trough divided into cells by plates formed of sheets of zinc and silver soldered face to face and cemented into grooves cut at regular distances in the trough sides. But these cells were difficult to clean and persisted in leaking, so that the scheme was abandoned, though the name *cell* has been retained and applied to the unit jar and its contents in place of the term cup.

In the course of these early experiments several important facts were noted. First, it was found that the action was more vigorous if the water in the cells was replaced with weak sulphuric acid; but then the zinc was rapidly dissolved even when no current was taken from the cell, hydrogen gas being given off at the zinc. To lessen the waste thus caused the cells were arranged in a *plunge*

battery, the metal strips or *plates* being attached to a frame so that all could be lifted out of the acid when the battery was not in use. This waste could be practically stopped, however, even when the plates were left immersed by rubbing the zinc with mercury or *amalgamating* it before assembling the cells, and with this improvement the way was cleared for a new theory of the action of the cell. For now, although practically no gas was evolved from the cells when no current was taken from them, a copious stream of gas appeared as soon as a circuit was completed between the end plates, and the zinc was consumed in proportion to the electricity used.

Was it not likely that the current of electricity was due not to the contact of the silver and zinc strips in adjacent cells, but to some chemical action between the silver and zinc strips and the liquid or *electrolyte* used in each cell? All the investigators recognized that somewhere in the circuit a force was produced capable of moving electricity through a closed path. The cells were indeed often called "electro-motors" or electricity movers, and the force was called electricity-moving force or "*electro-motive force,*" terms still in use today. True, the meaning of "electro motor" has gradually changed, until it is now almost always used to indicate a device for producing mechanical motion

from electricity, but electro-motive force, generally abbreviated to *e. m. f.*, is in constant use in our modern nomenclature in its exact original sense.

All scientists, then, were agreed as to the existence of an electro-motive force in the cell circuit; but as soon as the possibility of the chemical origin of this force was suggested by Fabroni the electrical world divided into two parties — one asserting that the real seat of force was at the junction of dissimilar metals as Volta had suggested; the other, that the force was produced at the contact of the electrolyte with the metal plates, or *electrodes.* After the most vigorous and voluminous controversy which has ever retarded the progress of electrical science, the chemical theory has finally prevailed, so that today we may think of the electric current as produced from the consumption of zinc in a cell, much as a current of air is produced in the inlet and outlet pipes of an otherwise closed room by a gas flame within. With the acceptance of the chemical theory, too, it becomes apparent that the convulsions of the frog-legs observed by Galvani were generally due to chemical action between the metallic part of the circuit and the juices of the frog tissues.

But entirely apart from the theory of the voltaic cell were the possible practical applications of electricity which might be found if a source of a really

continuous current could be developed. Even with the improvements in amalgamation and cell construction, however, the current from a simple cell rapidly decreased in strength. After much research this was finally traced to the accumulation of hydrogen gas at the copper plate, which produced an e. m. f. opposing the original e. m. f. of the cell, and which also obstructed the flow of current with a partially insulating layer of gas bubbles. A cell in this condition is said to be *polarized* and most of the modifications of the original design have been made in the attempt to get the hydrogen out of the way and allow the cell to furnish current until the zinc is consumed. One of the most successful schemes is to surround the copper plate, or the carbon plate (which is frequently used instead of copper) with some chemical which will combine with the hydrogen, thus keeping the plate free from gas. This method is applied in the Leclanche cell frequently used for ringing bells. Here the carbon plate is packed in a mixture of manganese dioxide and gas carbon contained in a porous cylinder, a similar arrangement being used in most of the dry cells; but although the manganese dioxide serves to depolarize the cell, the action is slow, and this class of batteries can be used only for intermittent service, where considerable periods of rest permit the de-

polarizing agent to act. In the Edison-Lalande and Gravity cells the materials are so arranged that the action of the depolarizer produces metallic copper which is deposited on the copper electrode, thus keeping the copper surface fresh and obviating any obstruction of the current by waste products. The depolarizing action in these cells is so perfect that batteries will furnish almost constant current continuously until the zinc is used up. For many years the Gravity cell supplied the current for the telegraph systems of the world. But zinc is at best an expensive fuel; and, with the development of electric generators, the voltaic cell, or *primary* battery — as it is frequently called because the current results directly from chemical action — has been relegated to those uses which require small currents at infrequent intervals.

Beside the idea of electro-motive force, the voltaic cell, with its continuous current, created the necessity for many fundamental conceptions in electric science. Our ultimate idea of any force is that of a pressure, and the electro-motive force is, therefore, conceived as an electrical pressure tending to cause an electric current to flow in any continuous or *closed circuit.* If the path is broken at any point the pressure still exists, but no current can flow as long as the path is an *open circuit.* Now a current and a pressure both have a definite

direction; and, although the early investigators had no experimental ground for deciding which direction the current from a battery actually took, they called the copper plate the *positive pole* of the battery and declared that the current should be considered to flow in the external circuit from this positive pole to the negative pole or zinc plate. Within the cell, of course, the flow is, therefore, represented as being from the zinc to the copper.

As the current is necessarily in the direction of the pressure, the e. m. f. of the cell is taken as being toward the negative; or (since in the older science of electric charges a body with a positive charge was said to have a higher *electrical potential*, and one with a negative charge a lower potential than neutral bodies) the positive pole of a battery is declared to be at a higher potential than the negative and the pressure of the cell taken as the *potential difference* between the poles. When the cell is on an open circuit the pressure or potential difference at its terminals is identical with its e. m. f.; but as soon as a current is allowed to flow, a part of the electro-motive force is consumed in forcing the current through the electrodes and electrolyte, and the pressure which reaches the terminals is, therefore, less than the true e. m. f. Furthermore, the amount of e. m. f. consumed depends on the strength of current which flows;

and, to Volta and his contemporaries, the relations between current strength and pressure seemed most confusing.

But the confusion was only apparent--the beautiful simplicity of the relations was soon be demonstrated in such final form by Dr. George Simon Ohm that Ohm's law, as it is called, remains and will probably always remain one of the fundamental expressions of our understanding of electricity.

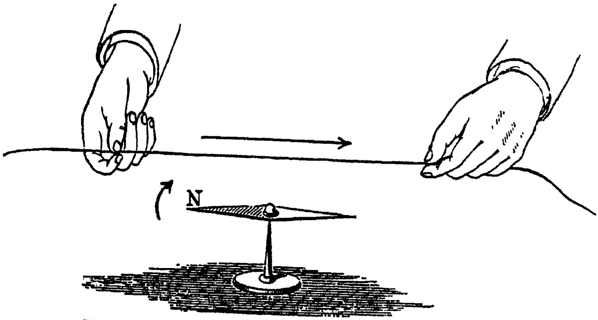
IV

"THE ELECTRIC CONFLICT"

THROUGH all the early period of experiments upon electricity and magnetism some relation between these two mysterious sciences was suspected. The earliest philosophers indeed believed magnetic and electric attractions to be identical, and even after Dr. Gilbert had shown the many points of difference the elements of similarity were striking. Furthermore, each advance of the pioneers brought to light some new fact which strengthened the suspicion of relation; as, when Franklin noted that steel objects struck by lightning were sometimes found to be strongly magnetized, and that a steel needle could occasionally be magnetized, though with an unpredictable polarity, by discharging a Leyden jar along its axis. Thus, when the invention of the voltaic cell was announced, the new possibilities of discovering the relation attracted various experimenters. Single cells were suspended in the hope that each would come to rest with some definite position in relation to the points of the compass; or very sensitive compass needles were used

to detect any magnetic attraction which the poles of the cells might possess. But all these experiments, performed on the electric charge of open-circuited cells, failed. Accumulated electricity at rest on a conductor has no magnetic effect.

Among the men especially interested in establishing the suspected relation was Hans Christian Oersted, professor of physics in the University of Copenhagen. To him came the idea that perhaps some effect of the electric current on the magnetic needle might be shown. Dilating on his pet idea to his assembled students one day in 1819, he chanced, by way of illustrating his remarks, to hold a wire, connecting a rather powerful battery of cells and carrying, therefore, a considerable current, just over and parallel to a large magnetic needle which had come to rest in the normal position on the lecture table. Imagine the excited delight of the staid professor and his students when, before their eyes, the needle slowly swung aside, tending toward a position at right angles to the wire! For the next few weeks, Oersted devoted himself to trying the effect of all possible positions of the wire with relation to the needle. If he reversed the direction of the current the needle deflected in the opposite direction; if the current direction remained unchanged but the wire was moved from above to below the needle, the direction of deflection also



Oersted's original experiment—the magnetic action of "the electric conflict"

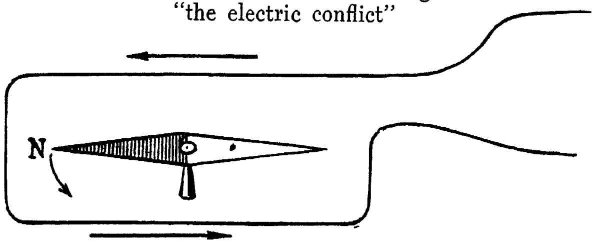
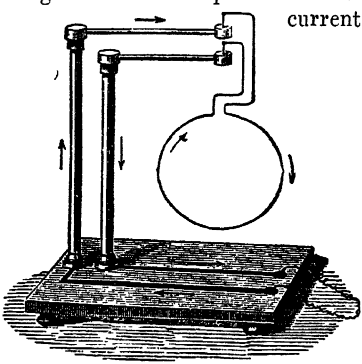
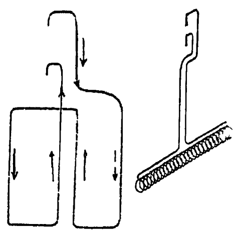


Fig. 1. The multiplication of the magnetic effect of a current by a winding "turn"



A



B C

Fig. 2. Ampere's table and coils used in his electro-magnetic discoveries

(a) Coil showing effect of earth's field on a current
(b) Coil neutralizing this effect
(c) The first solenoid

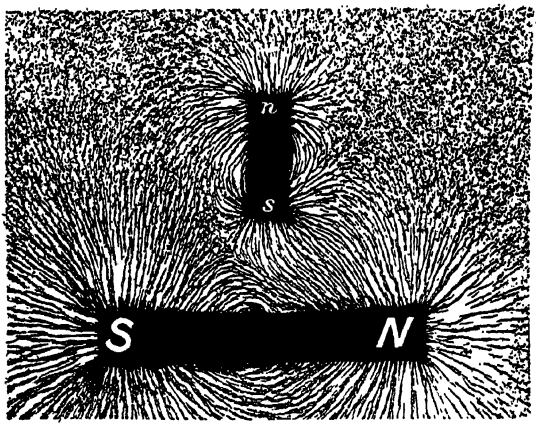
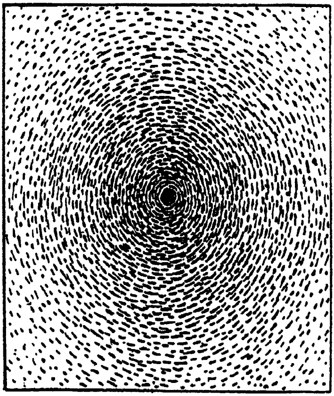
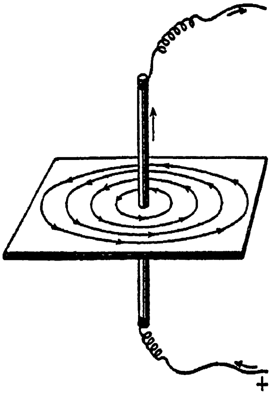


Fig. 3. Lines of magnetic force from two permanent magnets shown by iron filings [Page 53





(a) Iron filing diagram of magnetic lines in plane perpendicular to axis of a conducting wire, and (b) relation of direction of movement of north magnetic pole to direction of current flow

[Page 55

reversed. These and many similar facts he observed carefully and published in July, 1820, under the title "Experiments on the effect of the electric conflict on the magnetic needle."

News of the discovery traveled over Europe with remarkable rapidity and everywhere quickened scientific interest in electricity. André Marie Ampère, professor of mathematics in the Ecole Polytechnique of Paris, repeated the experiments carefully, and in less than two months after Oersted's publication, presented a complete theory of the phenomena. His first result was the famous rule for the direction of movement of the needle in Oersted's original experiment. "Imagine yourself swimming in the wire in the direction of the current and facing the needle, then the north pole will be deflected toward your left hand." From this rule it is evident that if the wire is bent over and back beneath the needle so as to form a rectangle, as in Figure 1, the effect of the current in the lower side is added to that in the upper, and about one-half the current will produce as much effect as the total current in the original experiment. By continuing the process and carrying the wire say ten times around the needle, or making a *winding of ten complete turns*, one-twentieth of the original current will produce the same deflection; and so on for greater numbers of turns. In this device, invented

by Schweigger in 1820, we have available a very sensitive means of detecting or measuring almost infinitesimal currents of electricity. It was called at first a "multiplier" from its action in multiplying the magnetic effect of any given current; as the instrument was improved, however, and came to be used for measurements it was renamed the *galvanometer*, and in this guise it is one of the most important of electrical measuring instruments.

But Ampère's contribution to electricity did not stop with his "swimmer" rule. After verifying Oersted's work he began original investigation. If the current caused a pivoted magnet to move, why should not a magnet move the current, why should not the magnetic earth move a conducting wire? To test this he constructed the wire rectangle shown in Figure 2A, which could be supported through conducting contacts in mercury cups so as to turn freely about its axis. When the plane of the rectangle was placed parallel to the normal direction of the compass-needle and a current sent through the wire, the rectangle immediately turned to an east and west position; and, when a magnet was held near it, it behaved as though the face of the rectangle toward the north were a north magnetic pole, and that toward the south a south magnetic pole.

The next step was almost self-evident, for, if a

current affected the magnet and the magnet affected another current, evidently one current should affect another. As his first rectangle was controlled by the earth's magnetism, however, Ampère prepared a double rectangle, shown in Figure 2B, in which the two halves were influenced equally but in opposite directions by the earth, and which, therefore, was entirely free to turn under the influence of any magnetic body affecting one side more than the other. With this and a current-carrying wire which could be held parallel to one side of the double rectangle, Ampère made his cardinal discovery: that *currents in opposite directions repel, and currents in the same direction attract each other.* Taking these experiments as a basis he developed his theory that magnetism is always the result of currents of electricity caused by unknown forces to flow around the circumference of the individual particles of which the magnet is composed — a theory especially important because it led him to construct the long spiral coil of wire called a *solenoid,* shown in Figure 2C, which, when suspended from the mercury cups and connected to a battery, exhibited all the characteristics of a magnet.

The importance of the solenoid became evident in 1825 when Sturgeon found that a cylindrical bar of iron placed within it acquired a magnetic

strength many hundred times that of the solenoid alone, and that when the current ceased, the magnetism of the core disappeared. Magnetism under control — brought into existence by the mere closing of a battery circuit, and instantaneously destroyed when the circuit was opened — magnetic attraction easily produced even as early as 1830 in such strength that a 60-pound magnet wound with 700 feet of wire and supplied by a few cells of battery could support a ton weight — entirely changed the possible future of electricity. These *electro-magnets*, as the cored solenoids were christened by Sturgeon, at once took a place in nearly every new electrical development, and today are vital parts of practically all electrical apparatus.

The polarity of an electro-magnet is at once known by applying Ampère's rule if the core is considered the magnetic needle. Facing the core and swimming with the current, the north pole will be found to the left. Perhaps a simpler rule to remember is that when facing the south pole the current is flowing around the core in a direction similar to the movement of the hands of a clock — or in a *clockwise* direction.

So much for the observed results. But how can we conceive of the action which causes them? How does a current flowing through a wire spiral make a magnet? and how does that magnet attract

iron? Michael Faraday, the greatest of English physicists, attacked these problems in 1830, and with his *lines of force* succeeded in producing a theory which, although it does not, of course, tell us what magnetism really is, is such a simple method of accounting for all the phenomena that it forms the easiest way of remembering the facts.

In the sixteenth century, and perhaps even earlier, it had been observed that if a magnet were covered with a thin smooth board or other stiff sheet of non-magnetic material and then fine iron filings sprinkled on the sheet, the filings arranged themselves in very definite curved lines radiating from the two poles and curving around until the lines from opposite poles joined as in the region below the large magnet in Figure 3. Faraday repeated this experiment with almost every conceivable modification and found that if two or more magnets were used, no matter what their relative positions, the lines from opposite poles always tended to join and those from similar poles to repel each other. He also found that these lines represented the path which a north pole placed at any point on the sheet would follow in moving toward the south pole of the principal magnet and that a small compass needle pivoted anywhere on the sheet took up a position tangent to the curve of the line passing through the pivot.

The space surrounding a magnet, then, said Faraday, may be best thought of as filled with invisible lines of magnetic force starting from the north pole, curving around through the air to the south pole, and returning through the body of the magnet again to the north pole. These lines are in tension along their length and mutually repel each other. Furthermore, the lines travel much more easily in iron than in air and try to crowd into any iron placed in their path. Now, anywhere that a line enters a magnetic substance a south pole is created, while a north pole appears at the point at which it leaves; hence a piece of iron placed near a magnet is pulled to the north or south pole by the tension along the lines crowding into it, according as more lines point directly toward one pole or the other. The stronger the magnet the more lines emerge from the north pole; and the stronger the magnetic effect at any region in space the more lines are passing through that region. Quite a resemblance all this bears to Robert Norman's "sphere of vertue," but in place of the vague ideas of Gilbert's day, Faraday sees his lines of force threading space, acting and reacting on one another with all the detail of a reality.

Applying now this same method to an electrical conductor, Faraday again found his lines of force, but this time the iron filings arranged themselves

in circles around the conductor in a plane at right angles to its axis. As Oersted had predicted the "electric conflict acts in a rotating manner"; and with his compass Faraday found that looking along the conductor in the direction of the current, the lines of force tended to move a north pole in clockwise rotation. In the compass, of course, the south pole tended equally to anti-clockwise rotation so that the needle merely turned until tangent to the line of force and did not revolve around the wire bodily. But Faraday had already developed an apparatus in which the current affected the north pole of a magnet only, and had thereby produced continuous rotation of the magnet — the first electric motor.

When Faraday made his iron-filing diagrams on parallel conductors he found that if the currents were in the same direction the adjacent circular lines of force tended to merge into a single line which, because of the tension along its length, pulled the conductors together; while if the currents were in opposite directions the repulsion of similarly directed lines of force caused the conductors to separate. From B, page 72, it is easily seen that as current flows in opposite directions in the two sides of a loop, the lines of force shown are practically those from one turn of a solenoid, and hence that the lines of force outside a solenoid

are very similar to those outside a magnet, while the parallel lines inside the solenoid are exactly those assumed to exist within a magnet.

The cause for the magnetic effect of the solenoid is thus apparent. But why the great increase in this effect when a soft-iron core is inserted? Modern theory accounts for this by assuming each molecule of the iron to be a natural magnet. Normally these molecular magnets are pointing heterogeneously in all directions, neutralizing one another; but when placed within the solenoid in the *magnetic field*, as any space filled with lines of force is called, the tiny magnets all turn easily into line like compass needles, and the effect of all the numberless north poles is added, as is that of the south poles, producing a single large magnet of great strength. As soon as the electric current is stopped and the directing field of force removed, the molecules again turn haphazard and the resultant total magnetism is zero. In the case of harder material, like steel, the molecules turn with greater difficulty, and once in line retain the position even after the electric current is interrupted. Thus steel becomes a permanent magnet after a single magnetization.

In his theory of magnetic lines Faraday thus produced a tool of remarkable power for electrical advance — a power which he used almost imme-

diately to develop the generation of electricity in an entirely new way, and thereby to make electric science the main ground of nineteenth-century progress.

V

AN ANCHOR RING AND WHAT IT HELD

"CONVERT magnetism into electricity." Thus briefly Michael Faraday noted, in his laboratory log book of 1822, one of the things he thought might be well worth doing. He could hardly have suspected the importance of the task. Indeed it would have made little difference could he have known that its performance was to place him foremost among experimental scientists and was to furnish the essential basis of the most marvelous practical applications of electricity. To him the mere joy of the discovery of scientific truth was quite sufficient incentive and reward.

Four times in the course of nine years he attacked the problem with long series of experiments, and each time had to close the careful record of his observations with the words, "No result." But intuitively he seemed to know that a solution was possible. A current flowing in a wire wound spirally around an iron bar made the bar a powerful magnet — why did not a magnet in a coil of wire produce a current in that wire? All his ex-

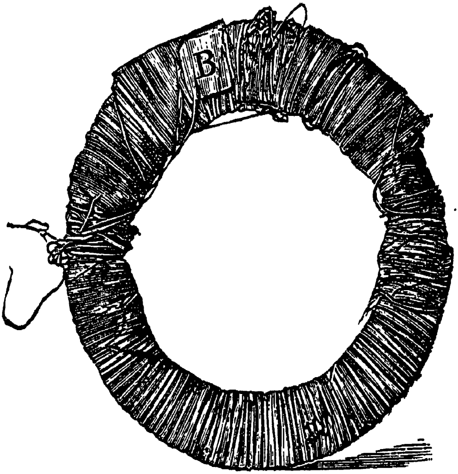


Fig. 5. Faraday's anchor ring with which he discovered the induction of electric current

(By special permission of the author and publishers of Dr. Fleming's "Alternate Current Transformer" Vol. I)

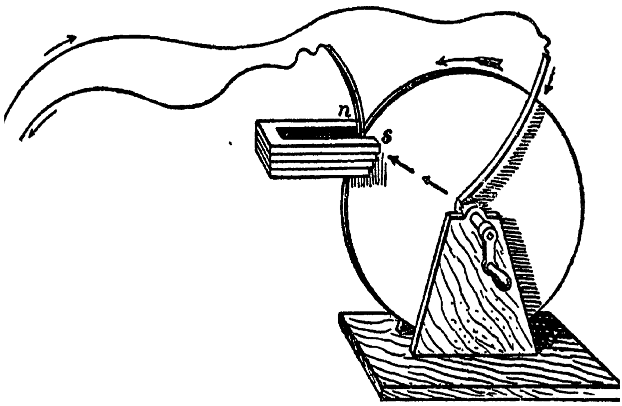


Fig. 6. The first electric generator producing direct currents

periments showed emphatically that it did not — still, he was unconvinced. During this period he carried a small model of an electro-magnet in his pocket and in leisure moments used the tiny bar with its encircling helix of insulated copper wire to concentrate his attention on the problem.

In the summer of 1831 for the fifth time he began to experiment. First he repeated all the experiments of his contemporaries which could possibly aid him — then he repeated all his own previous experiments and then — he struck out along a new line. In his note book he wrote:

"I have had an iron ring made (Figure 5), iron round and ⅞ of an inch thick, and ring 6 inches in external diameter. Wound many coils of copper round, one-half of the coils being separated by twine and calico; there were three lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. . . . Each was insulated from the other. Will call this side of the ring A. On the other side, but separated by an interval, was wound wire in two pieces, together amounting to about 60 feet in length, the direction being as with the former coils. This side call B.

" . . . Made the coils on B side one coil, and connected its extremities by a copper wire passing to a distance and just over a magnetic needle,

. . . then connected the ends of one of the pieces on A side with the battery. Immediately a sensible effect on the needle. It oscillated and settled at last in original position. On breaking connection of A side with battery, again a disturbance of the needle."

Nine years of thought and experiment, and then — "a sensible effect on the needle." At last he had the key; there was no effect while the current was flowing steadily through the coil A — while the magnetism of the core was constant and at rest with respect to B; it was only when the magnetism was changing from zero to its normal value at the instant the current began to flow through A, or changing back to zero when the current through A was interrupted, that a current appeared in B. Considering this in the light of his conception of lines of magnetic force, what did a change in magnetism mean to Faraday? What happened when the core was magnetized? Evidently lines of force suddenly permeated the core — that was the only change in the region of the B coil. The current appeared at the instant the lines linked through the coil and again when the lines disappeared. *Moving lines of force* then seemed the necessary condition.

Faraday perhaps did not get this full conception until some years later, but he must have had it at least dimly, for in his next experiment he con-

nected a coil of wire wound on a hollow spool to his galvanometer and then thrust a permanent magnet into the opening. Again the galvanometer deflected while the magnet was moving, or while the lines of force were cutting across the coiled wire, the first throw of the needle being in one or the other direction according as the magnet moved in or out. And again no effect was produced while the magnet was stationary. Of course it was immaterial whether the magnet or the coil moved — relative motion only being requisite — and hence the next step seems obvious. Forming a loop in a wire connecting the ends of his galvanometer winding, Faraday thrust this quickly between the poles of a very powerful electro-magnet — cut the lines with his conductor, that is — and as before got unmistakable galvanometer deflections. This experiment probably gave him the inspiration for constructing a device which he called "a new electrical machine."

A disc of copper was mounted as shown in Figure 6 on a conducting axle and arranged to be turned between the poles of a strong horseshoe permanent magnet. The edge of the disc and a portion of the axle were carefully amalgamated and strips of lead adjusted to make sliding contact on the amalgamated surfaces. As the disc was turned, the successive radii connecting the axle with the

point of the edge in contact with the outer lead strip or *brush* became virtually successive wires moved through the magnetic field, and a continuous flow of current in one direction resulted. If the direction of rotation reversed, the current direction also reversed.

A new electric machine indeed!—quite a different type of machine from the rotating globes, cylinders and discs of glass which had previously borne the name, for here was a true electric generator producing—in a very small amount it is true, but nevertheless, *producing*—the same unidirectional flow of electricity which under the name *direct current* is supplying nearly all the electric cars and many of the lights and motors of this electric age. The currents produced in all Faraday's experiments by the relative motion of lines of force and electrical conductors he called *induced currents* from analogy with the magnetism induced in a bar of iron held near a magnet, or the electric charge induced in an insulated conductor held near a charged body. Just as in the voltaic cell the chemical action really produces an electro-motive force, which can cause a current to flow only when a closed circuit is provided, so in these induction experiments, the motion of the magnetic lines produces an *induced e. m. f.* in the conductor, which in its turn can cause a current only when some closed circuit is available.

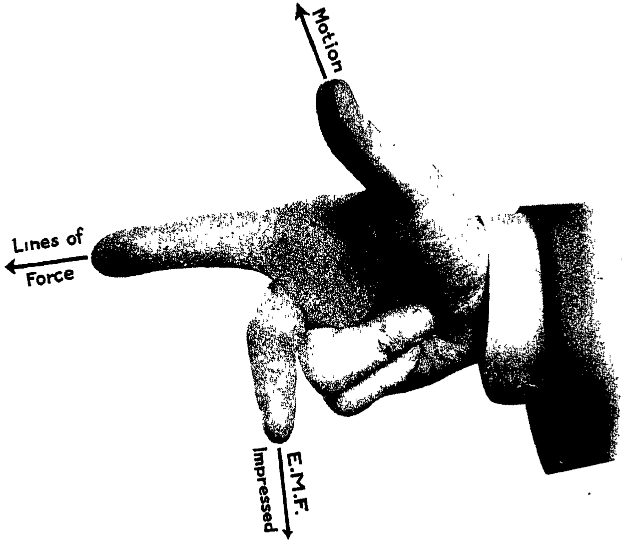


Fig. 7. Fleming's "right hand rule," showing the relation of the direction of the E. M. F. induced in a conductor to the direction of the motion and the direction of the magnetic field through which it moves

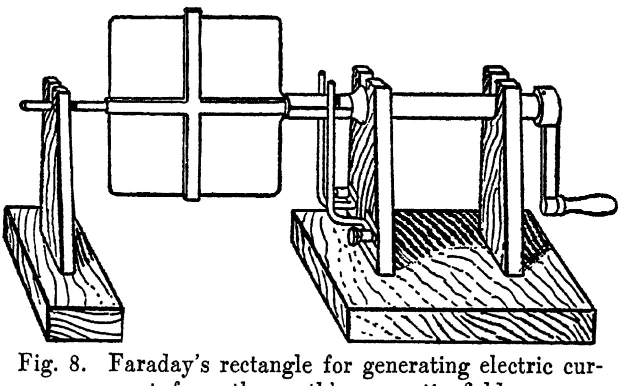


Fig. 8. Faraday's rectangle for generating electric current from the earth's magnetic field

The relation between the direction of the lines of force (always taken as from a north to a south pole in the space outside a magnet), the direction of motion of the conductor relative to the magnetic field, and the direction of the e. m. f. induced in the conductor can be deduced from Faraday's observations, but is best found in a given case by applying Fleming's "right-hand rule" (see Figure 7). Holding the thumb, forefinger and middle finger of the right hand so that each is at right angles to the other two, and placing the hand in such position that the forefinger points in the direction of the lines of force, and the thumb in the direction of the motion of the conductor, the middle finger will point in the direction of the induced e. m. f., and consequently, under closed circuit conditions, in the direction of the current.

Thus in Figure 8, which represents a rectangle of wire mounted on a wooden cross so that it can be easily rotated about a horizontal axis, suppose a north pole is held over the page and a south pole underneath, causing magnetic lines to pass through the paper from above, and suppose further that we slowly turn the coil on its axis. The side of the loop shown on top will have to move toward the bottom of the page; and applying Fleming's rule we find that the current will flow from left to right, while in the side of the loop now at the bottom

which will be moved toward the top of the page the current will flow from right to left. The opposite direction in the two opposite sides means of course the same direction with reference to the rectangle circuit, so that a *unidirectional* current flows around the loop during the half-revolution, if the ends are joined to make a closed circuit, but as soon as the side now at the top reaches the bottom and begins to ascend, the current ceases to flow from left to right and begins to flow from right to left, a similar reversal taking place in the other side. The current, that is, reverses each time the rectangle passes through the position where its plane is at right angles to the lines of force.

If each end of the wire forming this rectangular loop were connected to an insulated ring mounted on the shaft, and two brushes were arranged to make good contact on these rings while the loop was slowly rotated, a galvanometer connected so that its winding completed the circuit from brush to brush, would show a current reversing its direction at each half-revolution of the rectangle. This current would be a true alternating current — the only difference between it and the alternating currents which are used today in the transmission of thousands of horsepower over long distances being that in these the reversal in direction takes place about 50 times each second.

Alternating currents, however, appeared quite useless to Faraday and his contemporaries, for their ideas of current electricity were based on the continuous current from the voltaic cell. When, therefore, Faraday made this rectangle of Figure 8 to demonstrate that his induced currents could be produced directly from the earth's magnetic field he found it necessary to provide some way of causing the reversing currents in the loop to flow in a single direction in the external circuit, a process now generally called *rectifying* an alternating current.

For this purpose he mounted a cylinder of insulating material on the shaft concentric with its axis, and fitted a short length of brass tube tightly over this cylinder. He then connected the ends of the rectangle wires to the tube at points opposite one another and split the tube longitudinally along two opposite lines midway between the rectangle sides. Mounting two brushes as shown, and rotating the loop and split tube, either brush was placed in connection with one or the other side of the rectangle according as one or the other half of the tube came in contact with that brush, and the connection to the brushes reversed just at the instant the current direction reversed. The current through any external circuit connecting the brushes was thus continuously in one direction, and the loop of Figure 8 could be used as an alternating-current or direct-

current generator according as the coil was connected to *collector* rings or to this split tube arrangement called a *commutator*. This is indeed the essential difference between modern direct-current and alternating-current generators, machines which even in units of the enormous capacity of 27,000 horsepower represent only the normal development of Faraday's wire rectangle.

VI

THE UNITS

IN 1801, less than a year after Volta published his great discovery of the pile and crown of cups, two Englishmen, Nicholson and Carlyle, communicated to the Royal Society their observations on the effect of a continuous current from a Voltaic pile flowing between two electrodes immersed in a tube of river water. It had been discovered as early as 1790 that a Leyden jar discharge between metal points in a glass of water, decomposed a small quantity of the liquid into gaseous constituents, and probably Nicholson and Carlyle were only trying to find another proof of the identity of the two electricities, "frictional" and "voltaic," when they began their experiments. Not only did they succeed, however, in producing copious streams of gas from the electrodes as they had hoped, but the gases were entirely distinct, oxygen appearing at that electrode at which the current entered the cell and hydrogen at the other. In the Leyden jar experiment these gases were always mixed together — a

circumstance now well understood to be due to the fact that the Leyden jar discharge consists of an *electrical oscillation*, the current passing alternately several times in either direction during the almost infinitesimal interval of the discharge, but to the scientists of 1801 the difference in result seemed to indicate a difference in kind of electricity, and thus helped to delay the recognition of the fact that electricity from all sources is identical.

Still they had found a most convenient method of separating water into its components, and in 1805 a close friend of Volta, named Brugnatelle, substituted a silver coin for the negative electrode, a solution of gold for the water, and found that the electric current separated this solution into its elements and deposited a firm, even layer of metallic gold on the coin. This was the first example of *electro-plating*—the process used today in the jeweler's, engraver's and printer's arts being practically identical.

But, as in almost every branch of electrical science investigated before his time, it remained for Michael Faraday to amplify and show the real meaning of the discovery of *electrolysis*, as this decomposition of any substance by an electric current is called. In 1834 he became specially interested in developing some method of accurately measuring currents or quantities of electricity. When we

think of measuring a current of water we consider the quantity which flows past a fixed point in a definite time, and so it is easiest to think of measuring a uniform current of electricity by finding the quantity passing through a wire in a second. Some easily measured result of an electric current which bears a fixed relation to the quantity of electricity must, then, be found.

To investigate the relation between quantity of electricity and the resulting amount of electrolytic effect, Faraday developed his gas *voltameter*, consisting of two platinum electrodes immersed in acidulated water in a vessel so arranged that all the gas evolved would collect in a graduated cylinder. By a long series of experiments he proved that the quantity of gas was entirely independent of the size of the platinum electrodes, the amount of acid which he added to the water, or, indeed, of any other condition except the quantity of electricity which passed through the electrolyte. Furthermore, by trying solutions of various metals he found that the weight of metal deposited on the electrode by which the current left the electrolyte was in every case directly proportional to the quantity of electricity passing. Then by arranging in series a number of voltameters containing different electrolytes so that the same current necessarily passed through each, he discovered that the weights

of the different metals deposited, or of the gases evolved, bore a perfectly definite relation to each other, which could be easily computed from the weights of these substances that were equivalent in chemical combining power to a given weight of hydrogen. Here was the first proof of a definite relation between chemistry and electricity, a relation which today is generally believed to indicate an electrical cause for every chemical phenomenon.

No better method of measuring current precisely is known than this voltameter arrangement of Faraday. For rather complex theoretical reasons the quantity of electricity which will deposit on a platinum containing-bowl, 0.001118 of a gram of silver from a certain solution of silver nitrate has been taken as a unit, and if this unit quantity flows through a circuit in unit time, that is, in one second, the electric current is said to have unit strength. If the current is strong enough to deposit the 0.001118 of a gram of silver in one-fifth of a second, it is five times unit strength, and so on. This *unit* of *current* is named the *ampere*, in honor of the French philosopher. A rough conception of its magnitude may be obtained from the fact that the electric current flowing through an ordinary 16-candlepower incandescent lamp is about ½ ampere.

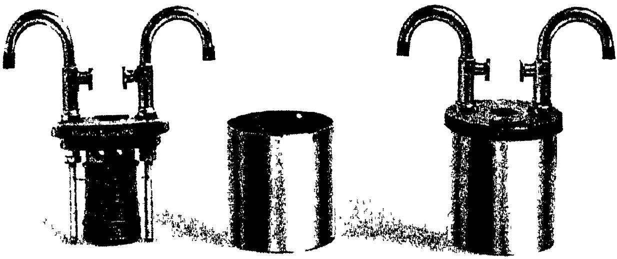
With this method of accurately measuring elec-

trical currents came the means of carefully checking the law announced in 1827 by George Simon Ohm to represent the relation between the current produced in any circuit and the electro-motive force or electrical pressure applied to that circuit. By a careful mathematical analysis of equally careful experiments Ohm had proved to his own satisfaction that if a certain e. m. f. applied to a given piece of wire produced a current value which we may call one unit of current, twice the e. m. f. would produce two units of current; one-half the e. m. f., one-half unit of current, and so on; or, in other words, that for any definite electrical circuit the current has a constant relation to the pressure producing it. The wire, that is, appeared to offer a constant obstruction to the flow of each unit of current, and Ohm named this obstruction the *resistance*. Further experiment showed that the resistance was proportional to the length of the wire, so that with a constant applied e. m. f. the current was halved by doubling the wire length, and that the resistance was also inversely proportional to the cross section of the wire, or the current was doubled by doubling the cross section. The resistance of each substance was found to be different, but for any given lot of one material the resistance always varied as the length and inversely as the cross section of the specimen and was entirely inde-

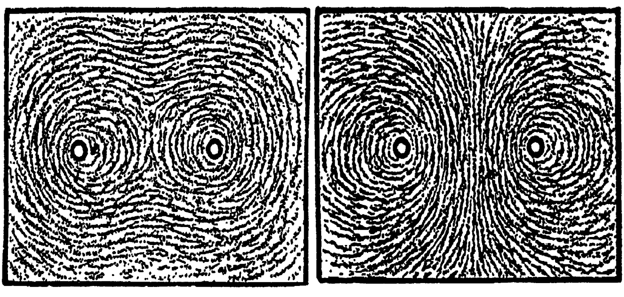
pendent of the amount of current flowing. Ohm expressed his law in the form: $\text{current} = \frac{\text{e. m. f.}}{\text{resistance}}$ and although his contemporaries scoffed, and later mathematicians termed his methods little better than a guess, this law stands today one of the simplest and most perfect statements of natural relations known in any branch of science.

The *unit of resistance* has been named, very appropriately, *the ohm*, and is equal to the resistance at 0° Centigrade, of a column of mercury of uniform cross section, 106.3 centimeters long, and weighing 14.4521 grammes. For all practical purposes, however, resistance standards are constructed of alloy wire, and carefully adjusted to correspond with the mercury standards preserved at the Bureau of Standards. These units of electric current and resistance of course represent the result of a vast amount of refined research following the original achievements of the pioneers, and this is also true of the unit of electrical pressure.

Electro-motive force was first conceived from the effect produced by a Voltaic cell, and it was, therefore, quite natural that the pressure generated by a single Daniels cell should be taken, about 1840, as the first unit of e. m. f. Along with the development of the various forms of cell, however, many experimenters had been working on the conception



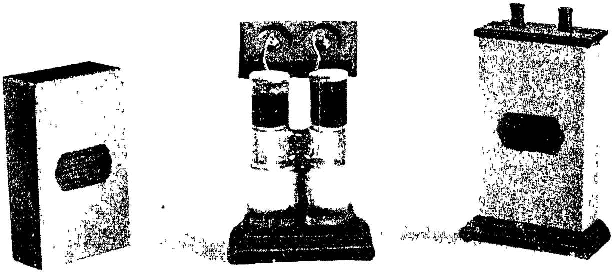
Standard 1-ohm resistance coil. Arranged for immersion in oil bath to secure constant temperature



A B

Arrangement of iron filings in plane at right angles to axes of two parallel conducting wires carrying currents (a) in the same, and (b) in opposite directions

[*Page 55*



Standard Weston cell. Adopted as legal standard E. M. F. January 1, 1911 [*Page* 75

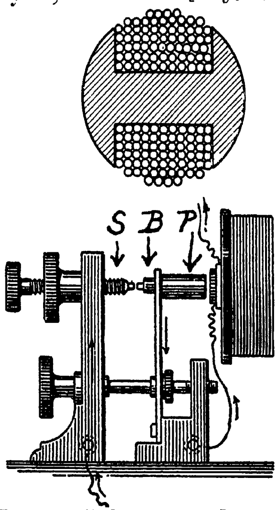


Fig. 9. Vibrator used in induction coils and in electric bells. Lower screw insulated from circuit portions

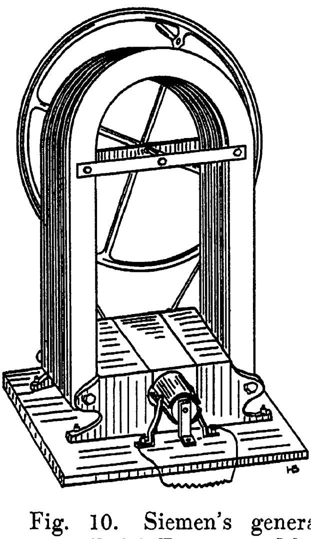


Fig. 10. Siemen's generator with shuttle armature, E. M. F. increased by increasing strength of magnetic field, turns in winding, and speed of armature revolution

of lines of force suggested by Faraday. In 1834 Lenz found that the electrical pressure induced in the B half of Faraday's ring, which we discussed in the last chapter, was directly proportional to the number of turns of wire in the coil — that is, doubling the turns in the coil doubled the induced pressure. It was soon found, too, that the ring form of apparatus could advantageously be replaced by winding the A, or magnetizing, coil directly on a straight bar of iron; so this part was simply an electro-magnet over which the B coil was wound as an outside cylinder of wire.

This modification led directly to the *induction coil*, in which the current is interrupted by the *vibrator* shown in Figure 9, and induced e. m. f.'s are, therefore, generated many times a second. As will be seen, the current is led through the stationary platinum-tipped-screw contact (S) to a similar contact on a flexible spring blade (B) equipped with a soft iron piece (P) opposite the iron core of the coil, thence through the flexible blade to the magnetizing coil, and then back to the battery. A current flowing magnetizes the core which attracts the iron piece on the flexible blade; but as soon as this piece moves toward the magnet the two platinum contacts are drawn apart and the circuit is broken. The core at once loses its magnetism, the iron piece flies back, the circuit is again made, and

the process is repeated as many times each second as the strength of the spring permits.

In experimenting with this apparatus it was soon observed that not only did the pressure induced in the outside or *secondary* coil increase with the number of turns in that coil, as Lenz had found, but it also increased with the number of times the magnetizing current was interrupted each second. Interpreting these and other facts in the light of Faraday's theory, Neumann in 1845 discovered the law that the pressure induced in any wire depends only on the rate at which magnetic lines cut it, or, in other words, on the number of lines of magnetic force crossing the wire each second. In the induction coil — since all the lines of force threading the core form closed loops extending from one end of the core to the other in the space outside — practically all these loops, all these lines of force, cut each turn of the secondary winding whenever the circuit is made and again when it is broken, and adding to the number of turns cut by a given number of lines is strictly equivalent to adding to the number of lines cutting one turn. Similarly, increasing the interruptions of the magnetizing or *primary* current, and thereby increasing the number of times per second which these lines cut the turns, is just the same as increasing the number of lines cutting the turns once each second.

In 1856 Werner Siemens applied these principles to the construction of the electric generator shown in Figure 10, in which a strong magnetic field is supplied by a group of permanent magnets of horseshoe form, and an iron core of shuttle-shaped cross-section is arranged to be rotated rapidly, by belted pulleys, in a circular opening between the magnet poles. Instead of a single turn of wire as in Faraday's rectangle, the core is wound with many turns, and thus the pressure, directly dependent on the number of lines cut per second, is greatly increased.

These various developments gradually changed the fundamental idea of electric pressure from that of a condition generated in a battery to that of the effect produced in a wire cutting lines of force, and so today we find the scientific definition of the unit of e. m. f. to be "the pressure produced in a wire cutting lines of magnetic force at the rate of 100,000,000 per second." This pressure is called *one volt*, in honor of Volta, and is very nearly that of the Daniels cell originally taken as the standard. The legal definition, however, is still given in terms of a battery, being derived from the statement that a certain cell invented by Dr. Weston, of Newark, N. J., has an e. m. f. of 1.08183 volts. Methods of measurement have been devised whereby the pressure of this cell is used as a standard, although

practically no current is taken from it, and under these conditions the cell voltage will remain constant over long periods of years.

The volt, the ampere, and the ohm have been so chosen that if the electrical quantities in any circuit are expressed in these units, Ohm's law is found to be fulfilled; that is, one volt pressure applied to the ends of a one-ohm resistance will cause one ampere to flow, or the current in amperes equals the pressure in volts divided by the resistance in ohms.

VII

THE SYMPATHETIC NEEDLE

THE application of magnetism or electricity to the transmission of some form of signals readily translated into words, seems to have been a favorite dream of even the earliest electrical philosophers. In the sixteenth century John Porta described, in apparent good faith, a "sympathetic" magnetic needle mounted to swing over a circular table about the circumference of which the alphabet was written — this needle causing another, magnetized from the same lodestone and similarly mounted, to move in perfect accord no matter how great the distance separating the two! If, then, the first was swung to point to any letter the second at once indicated the same letter, and thus, according to Porta, "To a friend at a distance shut up in prison we may relate our minds."

This telegraph, of course, like most of the scientific discoveries of the sixteenth century metaphysicians, was purely imaginary, and with our present knowledge of the limited space through which even the strongest artificial magnet produces

an appreciable magnetic field, the idea seems perhaps absurd; but, after all, it is not such a very different conception from that which has resulted in wireless telegraphy; and, without experimental verification, Porta's assertion is quite as credible as Marconi's. It served at least to direct the thought of electricians to the transmission of intelligence, and as each one of the great electrical phenomena was discovered, it was sure to be scrutinized by some one for adaptability to this service.

In 1753 a scheme was proposed for employing frictional electricity, in which twenty-six wires corresponding to the alphabet were to be strung on insulators from the sending to the receiving station, where each wire was to be equipped with a pair of pith balls suspended by linen threads. An electric charge imparted to any wire at the sending station would distribute itself along that wire and electrify the pith balls, causing them to diverge. This method was very slow, but with some slight improvements it was installed by Le Sage at Geneva in 1774, and thus ranks as the first working electric telegraph. The twenty-six wires proved difficult to maintain; and in a few years Lomond devised a system of signals, using a single wire with a sensitive pair of pith balls at each end of the line, the various letters being indicated by different numbers and magnitudes of divergencies.

The Voltaic cell suggested new possibilities. In 1812 Soemmering returned to the twenty-six wire scheme, his wires ending in 26 gold needles immersed in a trough of acidulated water; and the signal being sent by connecting a battery to any two wires, when the gases liberated by electrolysis in the trough indicated the two letters chosen, the order of the letters being determined by always reading first the needle liberating hydrogen. Ampère in his first work on Oersted's discovery described a telegraph to use twenty-six magnetic needles deflected by current sent over twenty-six circuits; and Gauss and Weber in 1833 improved this scheme by substituting a single heavy needle for Ampère's twenty-six, and a Faraday induced-current generator, consisting of a coil to be thrust over a bar magnet, for the unreliable Voltaic cells available at the time. This apparatus was actually installed at Göttingen; and it was while experimenting on improvements in the Gauss and Weber arrangement that Steinheil discovered, in 1837, that the earth could be used for the return circuit and that only one wire, therefore, was necessary.

The resistance between opposite faces of a cubic inch of earth is many times greater than for a cube of metal, and at first sight it might appear that the earth return would have such a high resistance as to

make it impracticable to send through it sufficient currents for long distance telegraphy. As we saw in the last chapter, however, the resistance of a conductor is inversely proportional to its area and while the area of a wire is strictly limited by the cost of the wire itself and of the supports necessary to secure it properly, the area of the earth circuit is almost unlimited, and its resistance is thus found to be negligible if a sufficiently good connection is made by burying large plates of copper in moist ground.

But although the German pioneers were thus making genuine advances, the first really successful development of Ampère's idea was made in England by Cooke and Wheatstone, who in 1837 patented the five-needle telegraph shown in Figure 11. Six wires were used in this system, and the needles were so deflected in pairs by sending a current through coils lying between them that the desired letter was found on the backboard above or below the needles at the spot to which the pair pointed. The control of these double deflections required the manipulation of ten switches or *keys* for opening and closing the various circuits.

Almost simultaneously with the patenting of this system, Professor Daniels announced his voltaic cell, which in the form of the Gravity battery completely filled the demand for a long-lived source of

constant electric-motive force. All the requisites for a commercially successful telegraph were thus at last available, and soon the 5-needle instruments were working in various parts of England.

In America, however, development had proceeded along quite a different line. Joseph Henry, working in his high-school laboratory, during the scant leisure of a teacher, had constructed electro-magnets of various forms and sizes until he had found that a magnet at the end of a long line of connecting wire, if wound with many turns and supplied by several cells of battery in series, had as great strength as the magnets previously made with a few turns and connected directly to one or two cells of battery. In modern terms this means that, according to Ohm's law, if the resistance of the circuit is increased by adding to the length of line, the e. m. f. must also be increased to maintain the same current; and that as the resistance increases beyond our ability to maintain the current with any reasonable e. m. f., and the current strength is, therefore, allowed to decrease, the strength of the magnet may be maintained by carrying the weaker current more times around the core. But although these laws had already been stated, few seem to have appreciated their significance and Henry's discoveries were discussed in the form first given. The electro-magnet then, if prop-

erly designed, could be energized from a battery at a distance—the application to telegraphy was obvious.

Some time about 1832 Samuel B. Morse, who two years before had seen in Henry's lecture hall an electro-magnet arranged to give audible signals and controlled through wires carried several times around the room, began to work on a scheme for making the magnet record the signals. After much hardship he produced, and exhibited publicly in 1837, the first recording telegraph instrument, shown in Figure 12. As will be seen, the battery circuit was closed when the metal arm on the end of the lever L dipped into the mercury cups at V, the motion of the lever being produced by running under the projection at N a rule in which "type," similar to those shown at 1 and 3, were set, each point on a type tilting the lever and producing a momentary contact in the mercury. The electro-magnet at E was arranged to attract a piece of iron, called an *armature*, fixed to the light swinging frame OB, which carried at B a pencil for marking a zigzag line on the moving strip of paper *r*, the shape of the line corresponding to the particular combination of "type" used. Morse claimed as his invention, the metal type signifying numbers, the recording mechanism, a code by which all common words were given representative num-

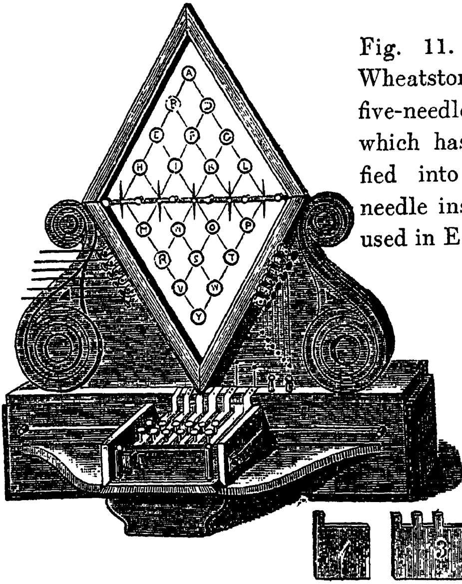


Fig. 11. Cooke and Wheatstone's original five-needle telegraph which has been modified into the single-needle instrument still used in England.
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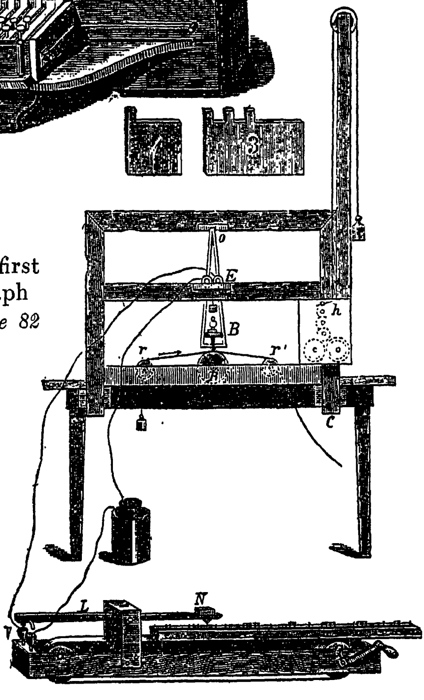


Fig. 12. The first Morse telegraph
[*Page 82*

bers, and a scheme for laying the wires underground in tubes — none of which are used in the so-called Morse system of today.

By 1843 Morse had gained sufficient influence to secure an appropriation of $30,000 from the United States Government for building an experimental line from Baltimore to Washington; this was completed, and the first message sent in May, 1844. In this line Steinheil's earth return circuit was used, and the line wire was at first carried underground; but the underground construction proved so expensive to maintain that the line was soon changed to an overhead wire on poles. The underground wire was the last of Morse's ideas to be abandoned. His partner, Alfred Vail, had substituted for the zigzag line recorder an apparatus in which the electro-magnet merely pressed a pen against the moving strip of paper for longer or shorter intervals, and this made a series of long and short marks, called respectively *dashes* and *dots*, separated by *spaces*. These marks represented directly letters of the alphabet and so spelled the words of the message without the cumbersome intermediate code of numbers; and the "type" and lever were replaced by a simple key, which closed the circuit when depressed by hand.

One essential to success, however, Morse had foreseen and provided. "Suppose," he wrote,

"that in experimenting on twenty miles of wire we should find that the power of magnetism is so feeble that it will move a lever with certainty but a hair's breadth; that would be insufficient, it may be, to write or print, yet it would be sufficient to close and break another or a second circuit twenty miles farther; and this circuit could in the same manner be made to break and close a third circuit twenty miles farther; and so on, around the globe." Here was the principle of the device which has since come to be called the *relay*, and which is now part of every telegraph station. For it was soon found that the more skillful operators of the original instruments read the messages from the clicks which the pen arm of the receiver made when pulled against the tape and when released — a considerable interval between clicks corresponding to a dash, a shorter interval to a dot. But at the best the clicks were very faint and required strained attention. Why not apply the relay as suggested by Morse to control a local battery in the receiving station, which, however, instead of sending the signal forward to another station should energize a powerful electromagnet to be called a *sounder*, making clicks loud enough to be easily heard? This system has proved so much more rapid than the recording apparatus, especially since the typewriter has come into use for taking the message, that tape recorders are now

rarely seen except in such special applications as stock "tickers."

The most usual arrangement of the modern telegraphic circuit is shown in Figure 13. When the line is not in use the switches Sw are closed at all stations, and current from the main battery B flows through the line and relay coils in series, and back through the earth. The relays R are thus magnetized and attract their armatures, closing the various local circuits and so energizing the sounder magnets S, which in turn draw their armatures against the lower stop. If now the operator at the left hand station wishes to send a dispatch, he opens switch Sw, breaking the circuit; the relays, and through them the sounders, are demagnetized, the sounder armatures fly up against the upper stop under the action of the control springs, and the operator by manipulating the key K closes and opens the circuit at will, a click in his own sounder and in that of each sounder along the line being heard at each *make*, and a slightly different click at each *break*. The line may theoretically be extended to include as many stations as desired by simply taking the wire from the key of the second station to the relay of a third, instead of to earth, and so on; but twenty-five stations in series have been found to give as much business as it is practical to handle over one wire.

Many complications have been added to this system to meet special needs. Several ways of sending two simultaneous messages over the same line, one in either direction, were devised before 1860. Thomas A. Edison made his first appearance as a notable pioneer in 1873 with an entirely successful method for sending two simultaneous messages in the same direction over a single wire. Edison and others have devised apparatus for sending over any line four simultaneous messages — two in either direction — and all these systems are in daily use on important lines. But the germ of all — the real pioneer electro-magnetic telegraph — was installed over eighty years ago to demonstrate to the high-school boys of Albany the curious facts which Joseph Henry had discovered during the summer vacation. Understanding these facts, the telegraph systems of the world seem but an inevitable development.

VIII

FROM TELEGRAPH TO TELEPHONE

GIVEN, the Morse Sounder with its armature vibrating slowly in response to signaling currents, controlled by the vibrations or movements of a sending key; and the increasing appreciation of the fact that all sounds were produced by vibrations of the sounding body, were transmitted by vibrations of the air, and were heard by vibrations of the ear drum; and it was almost inevitable that some one should sooner or later conceive the idea of making the key vibrate at the same rate as the air particles transmitting a sound, and thus through the action of the sounder armature start a new series of air vibrations at a distant point, or, in effect, transmit the sound by means of the telegraphic circuit.

As early as 1854 a Frenchman named Charles Bourceul saw the possibility of this application, and wrote: "Suppose a man speaks near a movable disc sufficiently flexible to lose none of the vibrations of the voice, and that this device alternately makes and breaks the current from a battery; you

may have at a distance another disc which will simultaneously execute the same vibrations." But Bourceul was content with stating his idea, and apparently made no attempt to construct an apparatus which should realize it.

Such an apparatus was constructed by Johann Philipp Reis, with beer barrel bungs, sausage skin, and bits of brass as materials, and in 1861 brought to such a state of completion that a description was published. In the original device a bit of metal was attached to the center of a membrane tightly stretched over a circular opening in a wooden frame, and a contact spring arranged to touch the metal centerpiece very lightly. An electrical circuit was connected to include the contact between the spring and centerpiece, and led through a battery and a light electro-magnet having a steel knitting needle for a core, mounted on a sounding box. This electro-magnet receiver was an idea of Reis's, based on the discovery of Professor Page, of Salem, Massachusetts, who had found that a distinct click, probably due to the rearrangement of the molecules, could be heard in the core of an electro-magnet suddenly magnetized or demagnetized. If then a musical note was sounded near the Reis transmitter the membrane was thrown into vibration, and the light contact of the metal center against the spring was broken as many times each

second as corresponded to the particular note, and in consequence a series of clicks of the same frequency, or in other words, a sound of the same pitch, issued from the receiver.

Unfortunately, it was only a note *of the same pitch* and did not necessarily resemble the sound to be transmitted any more nearly than a note from a tin whistle resembles the same note from a violin. This failure to transmit the quality of the sound proved fatal when it was attempted to use the Reis *telephone,* as he named his apparatus, for the transmission of speech. Even the natural prejudice of the inventor only produced the claim that "if you will come and see me here, I will show you that words also can be made out." The making out of an occasional word was not sufficiently practical to attract the attention of the world; Reis had only the meager resources of a poor German teacher, and thus his work was neglected and almost forgotten.

But the vision of Bourceul was still to be realized, although not quite in the way he outlined. In 1876 at the Centennial Exhibition at Philadelphia was shown a device having Bourceul's two discs vibrating simultaneously — a successful speaking telephone, the invention of Alexander Graham Bell. Professor Bell was unusually well prepared for telephone invention, as much of his life had been

spent in study of the laws of sound and of the voice, required by his work in teaching deaf mutes to speak. Early in the seventies he had been interested in telegraphy and had devoted himself to developing a system for sending any number of messages simultaneously over the same wire.

One scheme which he had devised for this multiplex telegraphy is shown in Figure 14. Here a continuous current flows through the sending and receiving magnets *energizing* or magnetizing the cores, and a series of watch springs (one pair only is shown) having different frequencies of vibration are mounted over the cores. With the springs at rest a steady current which may be indicated by the uniform height of the straight line marked "at rest," in the lower part of the figure, flows through the circuit. If now one of the springs over the sending magnet is "plucked" and thus thrown into vibration as it approaches the magnet core more magnetic lines pass through the magnetic circuit; while as it recedes from the core the number of magnetic lines decreases; and this movement of lines of force across the winding of the magnet causes an alternating e. m. f. to be generated in the coil which periodically aids and opposes the e. m. f. of the battery in the circuit. As a result the current through both the sending and receiving magnets is now represented by the height of the

wavy line in the lower figure—which simply means that the current varies with the passage of time as the height of the wavy line varies when we pass from left to right of the figure. In other words, the receiving magnet is strengthened and weakened as many times per second as the sending spring vibrates, and in consequence that receiving spring which has the same natural frequency—or would vibrate the same number of times per second if plucked—is thrown into violent vibration.

Bell's training in acoustics enabled him at once to appreciate that this method of transmitting vibrations might be so modified as to succeed where the make and break method failed—that is, in the transmission of "quality" of sound. For quality depends not on the frequency of the vibrations constituting the main tone but upon the lesser vibrations of higher frequencies superimposed upon this tone, so that while two voices sounding the note A would each produce 427 main vibrations per second, one might also produce simultaneously lesser vibrations of frequencies 520, 710, and 900; while the other might produce frequencies of 610, 780, and 840, resulting in entirely different qualities of tone. The make and break transmitter would tend to transmit only the main note, for it could vibrate at only one frequency at a time, but if the watch spring of Figure 14 were replaced with an elastic

diaphragm, Bell believed this diaphragm would vibrate simultaneously at all the frequencies required by voice quality.

Accordingly in his application for a patent on his cumbrous multiplex telegraph he included a claim covering the telephone shown in Figure 15, in which, for the watch springs, are substituted small soft iron armatures attached to membranes stretched over the openings of truncated cones appropriate for hearing and speaking. This form of telephone was constructed later and tried out in the course of the prolonged litigation over the Bell patents, and although very imperfect in comparison with our present instruments it could be made to transmit speech.

The "Centennial" telephone contained many improvements on Bell's original patent, but the first entirely successful Bell telephone was that covered by his second patent and shown in Figure 16. In this instrument he replaced the moisture absorbing membrane by a disc of thin "ferrotype" iron, and eliminated the necessity for a battery by magnetizing the soft-iron cores of his electro-magnets through direct contact with permanent bar magnets. He also greatly improved the distinctness of transmission by including a shallow air chamber between the diaphragm and the hearing orifice — all features retained in the receivers used

today which, indeed, are practically the same as these early Bell instruments.

In the figure the circuit is shown with the same earth return arrangement as is used in telegraphy, and most of the early telephones were so installed. But the telephone receiver is so much more sensitive than the telegraph relay, being affected by even one millionth of the current through an ordinary 16 candle-power incandescent lamp, that *stray* currents flowing through the earth from telegraph lines and from electric railway and other power circuits frequently produced such deafening noises that the ground return had to be abandoned and all-wire circuits used.

It was soon found, too, that whereas the magneto telephone was sensitive to almost infinitesimal currents when used as a receiver it unfortunately produced e. m. f.'s of equally infinitesimal magnitude when used as a transmitter, and that in consequence even the extreme delicacy of the receiver was insufficient to respond when the line length, and therefore the resistance of the circuit, became considerable, reducing the current in accordance with Ohm's law. Evidently, then, if long distance telephony were to become practical some means of producing stronger currents must be devised.

Almost before the demand was formulated, the *microphone*, the device which was to satisfy it, was

discovered by Professor Hughes, and independently rediscovered by Edison in 1878. One form of Hughes's apparatus is shown in Figure 17, and consists simply of two pointed blocks of carbon held lightly in contact by clamping-springs and mounted on a sounding board. If an electric circuit is taken through the carbon contact and thence through a battery and Bell receiver, any sound throwing the sounding board into vibration is loudly repeated in the receiver provided that the carbons are so adjusted that contact between them is never broken. This peculiar action of the carbon microphone contact is not yet entirely understood, but is believed to be due to the variation in the number of particles in contact as the carbons are pressed more or less closely together by the vibrations — more contacts giving more paths for the current or less resistance, fewer contacts giving fewer paths or greater resistance. The same effect can be obtained less perfectly with metal contacts, and it is probable that the words actually transmitted by Reis's telephone got through his metallic contact by this microphone action when adjustment was such as to prevent the vibrations causing makes and breaks.

At first, however, both Hughes and Edison believed the microphone action to be due to changes in the resistance of the body of the carbon, cor-

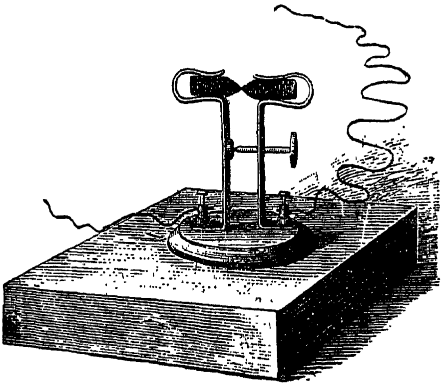


Fig. 17. The Hughes microphone on which the present standard transmitter is based

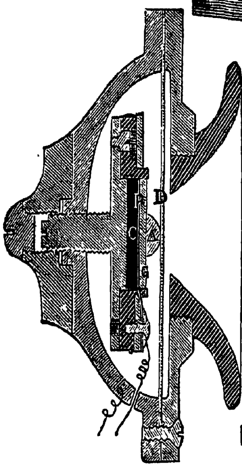


Fig. 18. An early form of Edison carbon transmitter

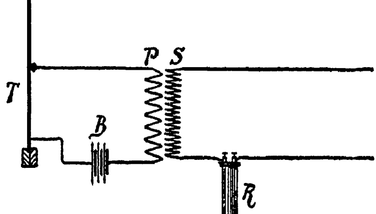


Fig. 19. Edison's application of the induction coil to long distance telephony [*Page 96*

responding to changes in the pressure, rather than in changes of the contact resistance; and acting on this theory, Edison constructed several forms of microphone transmitters. One of these is shown in Figure 18. In this apparatus the carbon block C is placed between a fixed metal back plate and a thin movable platinum plate P — these two plates forming the connection between the circuit and the carbon. The vibrations of the diaphragm are transmitted through the metal button A and glass plate G, and serve to vary the pressure upon C, or, according to the later theory, the number of contacts between C and the two plates. This transmitter and others constructed on similar lines proved to be capable of controlling much stronger fluctuating currents than could be generated in the simple Bell instrument. True, it was necessary to use a battery for the source of e. m. f. as in the original telephones, but with the carbon transmitter, increase in the number of cells resulted directly in increased distance of transmission; the battery, therefore, became an active element in the development.

As the view that the microphone action was due to contact resistance gained acceptance, the solid carbons of the new forms of transmitter were gradually replaced by various forms of small boxes or cells containing granular or powdered carbon —

each grain of carbon becoming one element in a tiny microphone and the number of contacts being thus indefinitely increased. Considerable difficulty was experienced at first from the tendency of the carbon granules to jam together or pack, but this has been practically overcome in various ways such as the introduction in the containing cell of perforated partitions, and today the granular carbon transmitter is the standard equipment for all long-distance telephones.

The success of these long-distance lines, however, depends largely on a third element introduced by Edison. For as the resistance of the line becomes considerable, even the rather wide variations in the resistance of the granular transmitter under vibration is a very small proportional variation in the total circuit resistance, and in consequence the fluctuations in the current are an equally small percentage of the current flowing through the receiver. To meet these conditions Edison arranged the connection shown in Figure 19, in which the transmitter T is only in circuit with a battery B and the low resistance primary winding P of an induction coil. The variations in the transmitter resistance now form a very large percentage variation in the circuit resistance and great fluctuations in the current are therefore produced. These fluctuations in the primary current, as explained in Chapter V of this

book, induce fluctuating secondary currents in the S winding of the coil, which pass out over the line and exactly reproduce every tiny tremor of the transmitter diaphragm in the diaphragm of the distant receiver R. That is, the line current is now only the fluctuating part of the transmitter current, and this fluctuation is much greater than when the transmitter is directly in the high-resistance line circuit.

The receiver, transmitter, and induction coil are of course merely the elements of the wonderful system of telephones which now makes the United States little more than a great neighborhood. In the central station switchboards, in the transcontinental lines, and even in the wall and desk sets are inventions of the highest order, made by pioneers whose individual names are lost in that of their company. But these must be left for the consideration of the specialist, being a result, rather than a part of the development, of the telegraph into the telephone.

IX

THE ELECTRIC ARCH

JUST when, where, or by whom the electric light was first seen is unknown. But whether a primitive man of the warmer zones first sufficiently overcame his fear of the growling thunder to look the storm cloud in the face and see the lightning flashes, or whether an inhabitant of one of the regions toward the poles had previously seen the beautiful electrical glow which we of the northern hemisphere call the northern lights, it is certain that the observation must have been made very near the beginning of things, and that electric light, next to that of the sun and stars, is the oldest known to man.

Of the electric light produced directly by man, however, the first record is found in the work of Otto von Guericke, the ingenious Mayor of Magdeburg, whose sulphur ball electrical machine is described and illustrated in the first chapter. After the ball was well rubbed with the palm of his hand Von Guericke found that in a darkened room a glowing light enveloped it, which increased with

further friction—but the analogy to the northern lights escaped him. In 1680, when this electric glow light had become one of the commonplace experiments, Robert Hooke observed a new phenomenon—"the more you rub it the more it shines, and any little stroke upon it with the nail of one's finger when it so shines, will make it seem to flash." This flash was the electric spark.

Sparks of greater and greater magnitude were produced as the electrical machines were improved, and the Leyden jar was discovered and developed, until in 1749, as we have seen, Franklin included in his analysis of the similarity between the spark and lightning, "Giving light, color of the light, crooked direction, . . . melting metals, firing inflammable substances, etc." Thus he recognized clearly that the electric discharge could supply both light and heat.

From this time on the spark took perhaps the foremost place among well known electrical phenomena, and it was most natural therefore that it should be one of the first tests applied to the product of Volta's cell to investigate the identity of the new with the old electricity. For some months no results were obtained. Wires even when brought very close together from the terminals of a cell generating one or two volts, refused to show any spark and the conviction gradually spread

that there was some essential difference between Voltaic and frictional electricity. We know now that a pressure of at least 35,000 volts is required to pass a spark through 1 inch of air, and hence, that the frictional electric machines which even in small sizes generate from 10,000 to perhaps 400,000 volts were the only early apparatus capable of producing sparks; but it was not until the time of Faraday that this view prevailed, and the identity of all forms of electricity was recognized. Although the early experimenters thus worked with batteries of insufficient pressure to cause sparks to jump across even the shortest distances in air, it was soon found that when a circuit through which a current was flowing was suddenly broken a tiny spark appeared for an instant at the break, and that this spark varied in color with the material of which the break contacts were composed. As larger batteries were constructed this new spark experiment was performed with more spectacular results, until in 1809 Sir Humphry Davy thought it of sufficient interest for a public demonstration, which was described in a contemporary work by Singer, as follows:

With a large apparatus employed at the Royal Institution, which extends to 2,000 pairs of 4-inch plates (2,000 cells of battery, that is), points of charcoal were brought within a thirtieth or fortieth of an inch of each other

before any light was evolved; but when the points of charcoal had become intensely ignited, a stream of light continued to play between them when they were gradually withdrawn even to the distance of near four inches. The stream of light was in the form of an arch, broad in the middle and tapering toward the charcoal points; it was accompanied by intense heat, and immediately ignited any substance introduced into it. Fragments of diamond and points of plumbago disappeared, and seemed to evaporate even when the experiment was made in an exhausted receiver; though they did not appear to have been fused. Thick platinum wires melted rapidly, and fell in large globules; the sapphire, quartz, magnesia, and lime were distinctly fused.

Even today a better description can hardly be given of the phenomena of the electric arch, or, as Davy subsequently renamed it, the *electric arc.* Only in one particular is there any mistake — the light did not come mainly from the arch of glowing carbon vapor which served to conduct the current from the positive charcoal point to the negative, but from the intensely hot point of the positive charcoal itself. Whatever the exact source of the light it was apparent that here was the possibility of an artificial illuminant far more brilliant even than the much discussed coal gas with which Wm. Murdock had but lately succeeded in lighting one or two houses in Birmingham. Inventors followed hard in the track of Davy, and various forms of mechanism were produced, but all these early attempts to design an *arc lamp* were far from suc-

cessful. Many difficulties were encountered almost at the start, for not only were the charcoal points consumed very rapidly, but a very considerable battery was required, and all the early cells were both expensive and most unreliable in action. The problem proved so complex, indeed, that illumination by coal gas forged ahead until by the very success of the gas industry one of the missing arc materials was provided, and electric lighting obtained a new impetus.

In 1840 Bunsen invented a process whereby finely ground carbon mixed into a paste with molasses could be molded into any desired form and then subjected to a high temperature, thereby producing rods or plates as desired. Now the carbon left in the retorts after the volatile components of the coal were driven off in the process of gas manufacture was found to be just the material required to form the finely ground carbon powder, and carbon plates made therefrom and used in an improved battery, also developed by Bunsen, gave a much cheaper and more reliable source of electrical current than any previously developed, while the same material molded into rods formed the slow-burning *arc carbons* still used in modern lamps.

In 1844, Deleuil and Archereau produced two lamps which were installed in prominent squares of

Paris and caused very considerable excitement; but after a few weeks' intermittent operation it was found that even should the mechanism be sufficiently improved to give promise of reasonably continuous service, the battery supply of electric current was still much too expensive for an economical light source. Again, then, progress was stopped by the need of an efficient electric supply, and again new inventions appeared opportunely. Electric generators were already in course of development from the early models of Faraday, and in 1866 a sufficiently satisfactory machine for converting mechanical rotation into electric current had been constructed to warrant the installation of electric arcs in a few lighthouses in England and France, and even the lighting of Prince Napoleon's yacht by electricity.

The mechanism of the arc lamp itself was still necessarily complex.

To start or *strike* the arc, the carbons must first be brought into contact and then gradually separated to that distance which is found best for efficient light production — in modern lamps from $1/8''$ to $3/4''$ according to the type of arc. Then, as the carbons are burned in the intense heat, just as coal is burned on a grate, the arc becomes longer and longer, and requires more and more voltage to maintain it, until a point is reached where the gen-

erator can no longer supply the necessary pressure, and the arc goes out, or, if the generator pressure is sufficiently high, the arc consumes so much energy and sends out so much heat that the lamp is destroyed. Hence a mechanism must be supplied for moving the carbons together, or *feeding* the carbons, at such a rate that the best length of arc is always maintained.

In addition to these confusing requirements the early inventors were perplexed by one of the natural characteristics of the arc. In an ordinary resistance like that of a length of wire, which we discussed when referring to Ohm's law, a single definite current through the wire corresponds to a definite electrical pressure across it; or, if the pressure is increased, the current increases until a value is reached such that this new current multiplied by the resistance just equals the new pressure, and equilibrium is again attained. In the electric arc, however, the resistance is found to vary with the current. If pressure across the arc is increased the current increases, normally at first, but in so doing lowers the resistance so that the current still further increases, and thus still further lowers the resistance, the process continuing until the maximum current which the generator can supply is reached. In other words, the arc is *unstable*. Of all these difficulties the last was the first to be met

satisfactorily, a result achieved by connecting the arc lamps in series and supplying them from a machine so designed that only a predetermined value of the current was supplied, no matter what the resistance of the circuit. These machines are still used, the design being such that as the resistance of the connected circuit to the machine decreases the voltage supplied by the machine decreases proportionately, and *vice versa.* This means, of course, that as more lamps are added in series and thus more resistance introduced into the circuit, the pressure across the machine and the pressure supplied to the circuit increases, and thus the number of lamps supplied by one machine is limited by the maximum pressure for which a machine can be safely built or which can be safely used in cities.

But although the question of instability was solved quite early by Brush and others, as just outlined, the difficulties in striking and feeding the arc continued to impair the operation of arc lamps for many years, and it is only during the last decade that perfect operation has been attained. The fundamental principles were discovered by Hefner von Alteneck and embodied in the Siemens & Halske lamp constructed as shown in Figure 20. In this lamp the main current flows from L through the series coil R and thence through the lever ca

and carbons g h to L_1. The carbon g is held against h by gravity until current begins to flow, when the coil R pulls the iron core c attached to the end of the carbon lever ca, down into R by reason of the magnetism produced by R, and the arc is thus struck. As the carbons burn away the resistance of the arc stream increases, and since the current is maintained constant by the generator, the pressure from L to L_1 increases and more and more current flows through the coil T until the magnetic pull of this coil becomes sufficiently strong to raise the core c. As this core rises, however, the arc length is reduced and thereby the pull of coil T gradually decreases until a condition is reached such that the drop across the arc is just sufficient to maintain the current through T which is required for the corresponding position of core c. By proper adjustments this position may be made to correspond to the desired arc length and the two coils or *solenoids* T and S will maintain an arc of constant length until the carbons are consumed.

Many improvements and modifications of this design have been made, until the arc lamp of today is one of the most effective of electrical devices. Prominent among the changes which have led to a notable advance is the use of an *inner globe* enclosing the arc in a confined space to which air is admitted very slowly, thus greatly restricting the

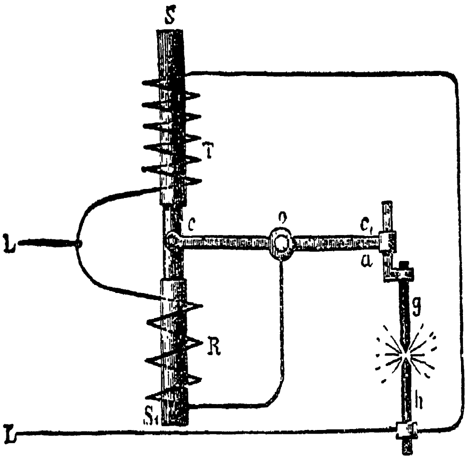
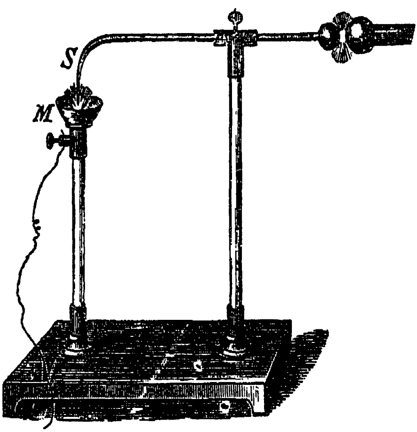


Fig. 20. Mechanism of the first successful arc lamp



The first electric heating device—a spark used to ignite ether

[*Page 108*

combustion of the carbons and thereby decreasing the rate of consumption to about one-eighth of that in the open air. These *enclosed arcs* require *trimming* or replacement of the burnt carbons only once a week instead of every day, and this longer *life* greatly decreases the expense and bother of maintenance. More recently the so-called *flaming arcs* have been developed in which the carbons are impregnated with various substances which pass into the conducting arc stream and render it very highly luminous, thereby increasing the amount of resultant light several hundred per cent. A particularly efficient arc has been invented by Dr. Steinmetz — the luminous arc — in which only one electrode is consumed, this electrode being formed of iron and titanium compounds giving off a beautiful luminous gas and having an extremely long life.

The stream of light from Davy's arc has thus spread and intensified until it has become one of the necessities of modern city life, but in the meantime what has been done with the characteristic which apparently most impressed Davy and his contemporaries, the intense heat of the arc?

X

THE HEAT OF NIAGARA

SOME relation between heat and electricity began to be suspected about the middle of the eighteenth century when amateur scientists everywhere eagerly took up the fascinating experiments made possible by the discovery of the Leyden jar. The fine ladies of London crowded the rooms of the Royal Society to see tiny dishes of ether or alcohol burst into flame when an electric spark was discharged near the surface of the liquid, or to watch with polite curiosity at the thinnest of iron wires melted to incandescent globules when an electric discharge passed through them. By 1749, four years after the discovery of the jar, "melting metals" and "firing inflammable substances" had become two of the best known attributes of the electric spark; but aside from the pregnant parallel which Franklin drew between these effects and those of lightning, no practical applications were made.

Sixty years later, 1809, the fine ladies of London again are crowding the lecture hall of the Royal Society, as did their great-grandmothers, to see the

wonderful change from electricity to heat; but now the experiments are performed by Sir Humphry Davy, and the results of the electric arc are not merely the melting of thin iron wires, but, as stated in the last chapter, "Thick platinum wires melt rapidly and fall in large globules; the sapphire, quartz, magnesia, and lime are distinctly fused." Electricity could produce temperatures in the arc entirely unattainable by any other means. Under the skilled guidance of Davy and his associates the new source of heat was employed in a few chemical investigations; but as in all applications of electricity, the voltaic cell was much too expensive for any extended practical use, and it was not until the production of the generator that the value of electric heat became apparent.

Progress was retarded too by the theory then prevailing as to the nature of heat, which was assumed to be an emission of tiny particles of a substance called "caloric." The electric spark or voltaic current in passing through a wire was supposed to disengage caloric from the substance of the wire, which caloric, striking the investigator's hand or some other temperature indicator, produced the effects of heat. Various investigations were undertaken during the first half of the last century to show the relation between quantity of electricity passing and quantity of caloric disengaged, but it

was not until 1842, when the Englishman Joule made his classic investigations on the relation between mechanical energy and heat, that the real advance began.

Joule first proved that if an apparatus were arranged so that a weight falling through a considerable height could be made to turn a paddle wheel in a vessel of water the temperature of the water would be raised and that the rise in water temperature always bore a fixed relation to the work done by the weight in turning the wheel. The quantity of heat necessary to raise the temperature of one pound of water one degree Fahr. being taken as one heat unit, this amount of heat was produced through the friction of the water by a weight of 10 lb. falling 77.8 feet, by a weight of 100 lb. falling 7.78 feet or by any other combination of weight and distance which gives 778 ft. lb. of work. The mechanical work done by a moving mass was thus shown to be exactly equivalent to heat; and as philosophers discussed this result they began to believe that the motion of the weight which produced motion of the paddle wheel could ultimately produce perhaps nothing but motions, and so came to be accepted the modern theory, that heat is a motion of the minute particles or molecules which are believed to compose all matter.

Having shown that the *energy* of heat, or the

ability of heat to perform work, was thus merely a form of the energy possessed by all moving bodies, from sand grains to cannon balls, Joule turned his attention to establishing the relation between heat and the electric current. For these experiments he used an apparatus which Lenz afterward modified to the form shown in Figure 21, consisting of a coil of resistance wire enclosed in a vessel of water with a convenient arrangement for passing electric current through the wire and for reading the temperature of the water. With this apparatus, called the current *calorimeter*, the first relation to be demonstrated was, that no matter what size or length of wire was used, no matter how small the current or how short the time of flow, some heat was always produced. In other words, no electric current can flow in any circuit without some of its energy being converted into useless heat and this *heat loss* is, therefore, inevitably present in every transmission line, in every house-lighting circuit, in every application of electricity. By careful measurements Joule finally deduced and Lenz verified the relation, now known as *Joule's law*, that the heat generated in a wire is proportional to the square of the amount of current flowing multiplied by the resistance of the wire and the time the current flows. That is, if we double the current flowing through a given wire we get four times as

much heat; if the current remains constant but the wire is made twice as long, thereby doubling the resistance, twice as much heat will be produced; while if resistance and current strength remain unaltered but the time of flow is doubled the quantity of heat will also be doubled.

It is important to understand this pioneering of Joule, for with electric current equivalent to heat, and heat equivalent to mechanical work, the relation between electric energy and mechanical work soon became evident. Expressed in abbreviated form, Joule's law is,

Heat = *Current* × *Current* × *Resistance* × *Time;*

but by Ohm's law, Current × Resistance = Pressure, so that we may rewrite Joule's law,

Heat = *Current* × *Pressure* × *Time;*

and as Heat produced means mechanical work done,

Work = *Current* × *Pressure* × *Time;*

or, in modern electrical units,

Work = *Amperes* × *Volts* × *Seconds.*

The work that is done by electricity in forcing a current through a wire or any other electrical circuit thus is shown to be equal to the product of the pressure necessary to cause the current to flow, the strength of the current, and the time the operation continues.

In many cases, however, it is necessary to know

not only how much work is done, but how fast it is done — how much work is done in one second. Indeed, in stating the size of a steam engine or a motor or any other source of mechanical energy, the attainable *rate of work* or the *power* is generally the figure desired. Evidently this rate is the total amount of work done, divided by the time it takes to do it; or, since Work = Volts × Amperes × Seconds, the rate of work equals the product of the volts and amperes multiplied by the seconds and divided by the seconds, which is, of course, merely the product of the volts and amperes. Hence, we have finally,

Power = Volts × Amperes.

These statements are strictly true of all work and power relations in direct-current circuits, and of all heat production in alternating-current circuits, but have to be somewhat modified for alternating currents converted into forms of energy other than heat. This, however, introduces questions rather too complex for the present discussion; it is sufficient to remember that in alternating-current circuits the product of volts and amperes frequently shows an *apparent power* greater than the *true power*.

The unit rate of work is taken as that obtaining in an apparatus where one volt is causing a cur-

rent of one ampere to flow, and this rate of work is called the *watt*. If work is being done 1,000 times as fast as this, the rate of work is said to be one *kilowatt;* and the amount of work done when this kilowatt rate continues for an hour is called one *kilowatt-hour*, and is used as the basis for selling electric energy. Very exact measurements have been made of the quantity of heat generated by one kilowatt hour of electrical work, and from these data, and those obtained in careful repetitions of Joule's original experiments on the heat units generated by a falling weight, the numerical relation of the electrical and mechanical units can be accurately computed. In this way it is found that a one-horsepower engine will do the same amount of work in one hour as will an electric generator producing 0.746 of a kilowatt hour, or that an electric power of 746 watts is the equivalent of the mechanical rate of work called one horsepower.

With the law connecting heat and electricity fully developed the production of apparatus suitable for converting electric current into heat became merely a question of mechanical design, as is attested by the many forms of successful stoves, cooking utensils, flat irons, soldering irons, and other devices now in use. In all this apparatus the heat as fast as it is generated is dissipated through conduction by the surrounding air or by radiation

to other bodies, or is absorbed by the material upon which work is being done; and in consequence the size of apparatus to be used for any process will depend on the rate of heat dissipation which must be maintained rather than on the total quantity of heat required.

In almost all electrical heating devices heat is produced in a wire or other metallic conductor having a high resistance per unit of length, and it has been found that the rate at which each unit length of such a wire gives off heat is proportional to its temperature. If then the rate of generating heat is gradually increased by forcing more and more current through the heating coil or wire the temperature of the wire will also increase until it reaches such a degree that the wire melts—an action exemplified in the *fuse wire* commonly placed in series with a circuit which it is desired to open when the current exceeds a certain value. More heat, however, can be dissipated per unit length if the wire is surrounded by a better heat conductor than air, and in many devices the coils are imbedded in enamels which serve not only to increase the rate of heat dissipation but also to insulate the various convolutions of the winding and to protect the hot wire surfaces from the attacks of atmospheric oxygen.

In all this class of apparatus the temperatures

produced are comparatively low, the great advantages of electric heat being found in the ease with which it is generated at the point of use, the absence of all the smoke or hot gases inevitably present with burning fuel, and the close control of temperature readily obtained by controlling current strength.

But electric heat has another field in which it is unique—the production of very high temperatures in the various forms of electric furnace. The most usual type of furnace, shown in Figure 22, is a direct development of Davy's experiment, the arc being formed between large electrodes just over a crucible containing the material to be heated and the whole enclosed in a small chamber with thick walls of heat-insulating material. A temperature of over 3,500° Centigrade, nearly twice that attainable in any fuel furnace, can readily be reached, and with this equipment electro-chemists have produced such substances as the abrasive carborundum; graphite of great purity; calcium carbide for the generation of acetylene gas; and the highest grades of steel. Some of these materials are made with greater economy in the resistance furnaces, in which the substance to be heated is used to carry the current, as shown in Figure 22½, and thus gradually raised in temperature to any desired degree. In this type also a heat-insulating chamber is used and

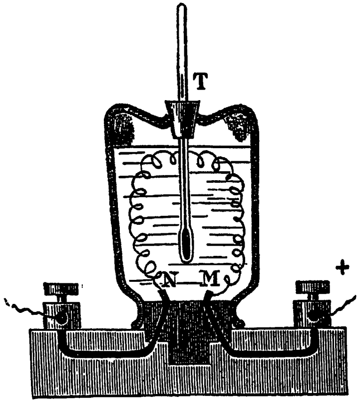


Fig. 21. Lenz's current calorimeter with which he verified the relation between heat and electricity

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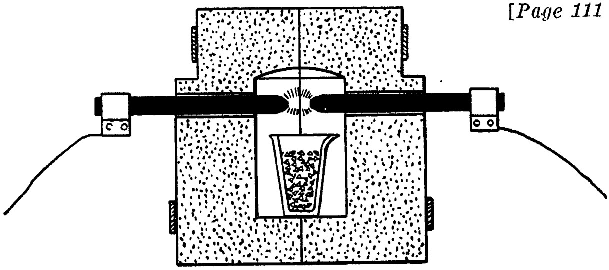


Fig. 22. The arc type of electric furnace

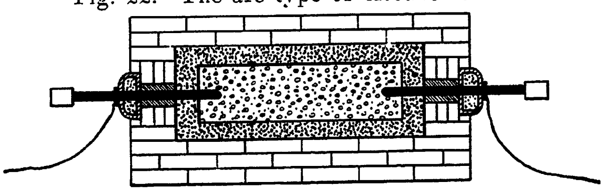


Fig. 22½. The first commercial application of electric heat. The Cowles resistance furnace

the temperature attainable is limited only by the melting point of the walls or of the electrodes used to conduct the current to the material.

A contemporary of Davy, after witnessing his demonstration of the heat of the arc, wrote that it was the most brilliant experiment in all science. Today the waters of the great lakes are performing this experiment at Niagara on a scale which results in a great industry, and to the laurels of the pioneers is added the development of electric heat.

XI

THE BAMBOO LIGHT

ANY solid substance will send out light if it is heated to a sufficiently high temperature, provided, of course, that it is not destroyed before the necessary temperature is reached. The experimental facts upon which this generalization is based began to be accumulated at least as early as the iron age, and for many centuries it has been one of the commonplaces of everyday life. No sooner, then, was it found that an electric current heated the conductor through which it passed than experiments were made in the attempt to develop sufficient heat to cause the conductor to give off light, and after some failures the prominent electricians of the latter half of the eighteenth century could show incandescent wires of iron, platinum, and even gold and silver.

Contemporaneously with the development of the electric arc light this second form of electric light claimed the attention of many inventors who endeavored so to arrange an incandescent conductor that it would withstand high temperature for a considerable time; or, in other words, have a sufficient

life to make possible its application as a commercial light source. As early as 1820 De la Rue enclosed a long spiral of platinum wire, as shown in Figure 23, in a glass tube from which the air could be exhausted, this exhaustion being intended to prevent any chemical action between the hot platinum and the oxygen of the air. But although the platinum spiral could be made to glow brightly for a few moments, it soon melted at one point or another and had to be replaced.

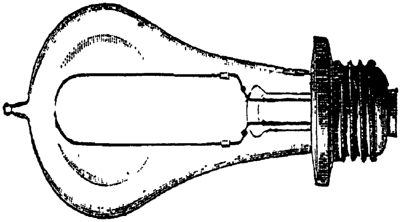
Platinum continued to be the favorite material for the incandescent conductor until 1845, when a young American, J. W. Starr, took out a patent in England for the lamp shown in Figure 24. Starr used a strip of carbon in the high vacuum existing at the top of a barometer tube. His lamp gave such promise that Faraday is said to have shown enthusiastic interest. After a successful exhibition of a candelabrum containing 26 of the lamps, one for each State in the Union, Starr, who was but 25 years old, died on his return voyage to America, and the commercial development of his lamp was given up. But he had clearly stated in his patent application that, "the metal found most advantageous to use is that which, while it requires a very high temperature for its fusion, has but a feeble affinity for oxygen, and offers a great resistance to the passage of an electric current";

and he had demonstrated the practicability of employing carbon, so that for the next thirty years carbon was the main subject of experiment.

Despite the numerous modifications which were made of Starr's lamp, however, and the frequent announcements of success which came first from France, then from England, then from Russia, and so on over the scientific world and back again, the real incandescent lamp appeared as far off as ever. Carbon seemed to have the property of self-destruction at high temperature, for with the best vacuum then obtainable the rods gradually disintegrated. In consequence complex mechanisms were arranged within the lamps to replace burnt out rods with new ones, and thus certain lamps were given a life of several hours! As the carbons required such frequent replacement it was necessary to provide globes which could be easily opened and, after replenishing the burners, easily exhausted; therefore the incandescent lamps made before 1880 are large, cumbersome affairs with clamps and rubber rings or cement-filled grooves for securing air-tight joints, and projecting stop-cocks for connection to portable air pumps.

And then came Edison!

Edison's attention was first seriously attracted to the problem of the incandescent light by the commercial success of the arc light, which by 1878 had



The bamboo filament Edison lamp

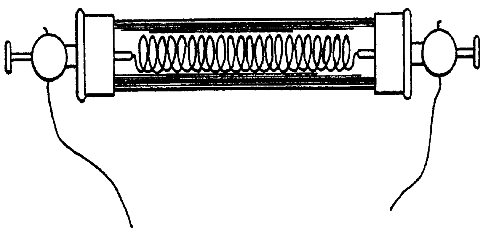


Fig. 23. De la Rue's platinum light

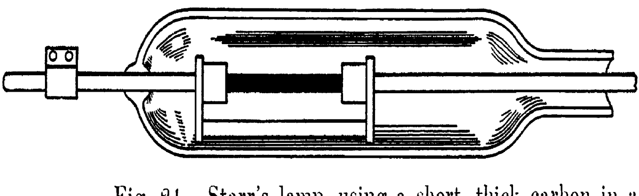


Fig. 24. Starr's lamp, using a short, thick carbon in a barometer tube

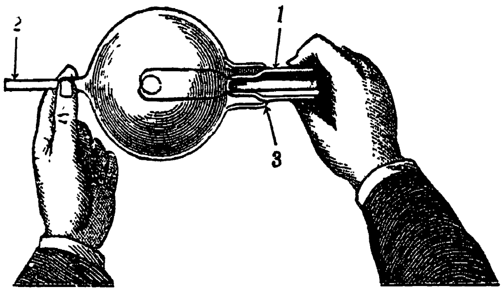


Fig. 25. Assembling bulb and filament for welding

[*Page 125*

Metallized carbon lamp [*Page 126*

taken its place, in this country at least, as the future street illuminant. To Edison it was evident that the lighting of small interiors, such as private rooms and stores, was a much more important field; and after an exhaustive study of the gas-lighting system he became convinced that this field could be successfully covered only by a system of small incandescent lights in which any lamp could be turned on or off entirely independent of any other. That is, instead of the *series system* which had been universally proposed heretofore and in which, as the current passed through all the lamps one after another, the failure of any one served to interrupt the circuit and thus extinguish all the lights, Edison decided to develop a *parallel system.* In this system each lamp would be connected between the pair of wires leading to the generator, so that there would be as many paths for current to flow from the positive to the negative wire as there were lamps connected, and the failure of a lamp would thus mean merely the interruption of one path and would not affect the other lights. With any of the lamps previously constructed a current of 10 amperes or more was necessary for incandescence; a parallel system of connection would therefore require enormous distributing wires, as each lamp added would increase the current in the main wire by 10 amperes, and a hundred lamps in parallel

would mean distributing wires capable of carrying 1,000 amperes or having a cross section of nearly a square inch. Hence, to make a parallel system practical, Edison must produce an incandescent light which would not only have a reasonable life but which would require much less current than any that had been even suggested as desirable.

In 1878 the attack began with experiments on tiny strips of carbonized paper raised to incandescence in a vacuum, Edison's idea being that in order to reduce the current required, it was necessary to reduce the amount of material to be heated, but these primitive paper *filaments* had a maximum life of fifteen minutes, and after weeks of effort he was disposed to accept the theory of the self-destruction of carbon. Turning to the investigation of platinum filaments in the fall of 1878 Edison concentrated his efforts on securing and maintaining a better vacuum, and in the course of certain trials on platinum sealed into a closed glass bulb he discovered that the life was greatly improved by heating the filament to incandescence during the process of exhausting and sealing. This has been found to be due to the fact that certain gases are attached to the surface of the cold wire and absorbed in its substance — or *occluded* — and that when the wire is heated these are given off, and, of course, in the older lamps they immediately de-

stroyed the vacuum. Even with these improvements, however, platinum had but a short life, for in order to get a fair light it had to be operated near its melting temperature. Returning to his carbon filament experiments to determine the effect of the new method of exhaustion and the use of an all-glass sealed globe, Edison, on October 21, 1879, produced a lamp having a filament of carbonized cotton sewing-thread sealed in a glass globe exhausted to a vacuum of one-thirty-thousandth of an atmosphere, which burned for *40 hours.* The old paper filaments were then tried once more and proved much better even than the thread, and arrangements for the commercial development of the lamp were at once begun.

In the course of these experiments Edison had found that although reducing the cross section of the filament reduced the current necessary to bring it to incandescence, as he desired, it also, of course, reduced the surface area so that the light given off per inch of filament length was decreased in proportion to the decrease in filament diameter. To get the amount of light which he intended, therefore,—sixteen-candlepower, or the equivalent of an ordinary gas flame—it was necessary to increase the length of the filament, and thereby its resistance, to such a degree that 110 volts were required by Ohm's law to force the necessary cur-

rent through the lamp. In this way the pressure of distribution was fixed at 110 volts — a magnitude which is still the standard.

The first hundred lamps were strung along the streets and in some of the houses of Menlo Park, soon to be famous the world over as the birthplace of the Edison lamp. On the last day of the year 1879, evening excursions from New York brought three thousand visitors to see the latest wonder — the light which was to be the chief factor in making this the age of electricity.

But although the paper filaments were most successful as compared with all preceding attempts; although the lamps gave a light about equivalent to that of an ordinary gas flame, required less than an ampere of current, and had a life of more than a hundred hours; although the greatest enthusiasm soon prevailed throughout the world of science and the problem was declared finally solved, Edison was not satisfied. The life of the lamps was still too short — the behavior of different lamps was not sufficiently uniform. Night and day he and his assistants worked, trying every conceivable form of paper and vegetable fibres until several thousand different materials had been made into filaments, tested, and found no better than the original paper. And then one day, in the spring of 1880, he noticed the strip of bamboo used to bind a palm-leaf

fan. Straightway he made filaments out of that, and thus discovered the material which was used for the several millions of lamps manufactured during the next nine years. Having found bamboo to be good, this great electrical pioneer enlisted other men dominated by the world-old pioneering spirit to go to every bamboo-producing part of the earth and find that bamboo which was best. Japan, Southern Brazil, Jamaica, Cuba, the swamps of Florida, the unknown jungles of the farthest Amazon were all searched, and cases upon cases of specimens were sent back for test, the number of filament materials investigated nearing 6,000, when, in 1889, just as the latest explorer returned with reports on the bamboos of India and the Malay peninsula, the laboratory pioneers produced an *artificial* filament material which proved better than any natural fibre and the use of bamboo was gradually discontinued.

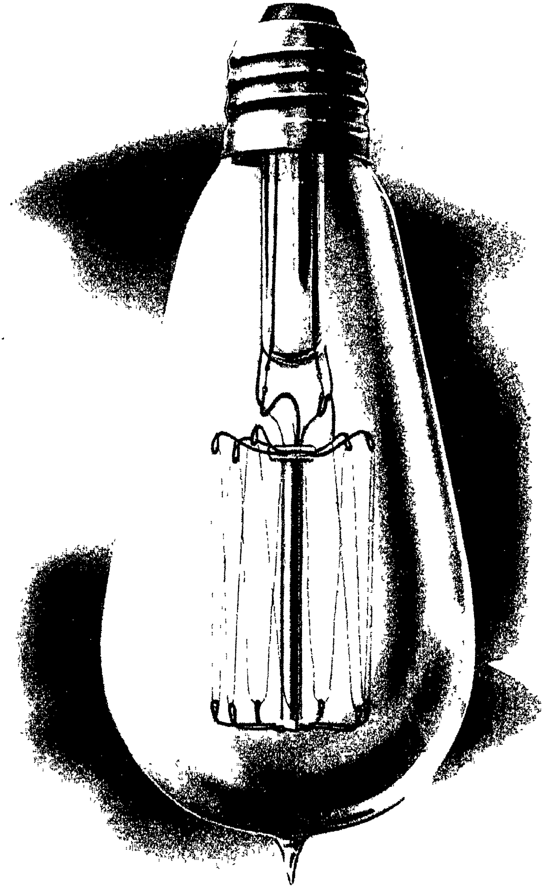
All carbon lamps made today are of the artificial or "squirted" filament type; the process of manufacture is partially illustrated in Figure 25. Some natural cellulose fibre, such as cotton, is dissolved in a suitable liquid, and the solution, having about the consistency of molasses, is squirted under pressure through a fine hole into another solution which immediately hardens the thread of cellulose. This tough thread is then cut to the proper lengths and

wound on forms to the shape desired for the finished filaments. Forms and cellulose threads are next placed in ovens and the cellulose carbonized, resulting in carbon filaments of standard size and of approximately uniform cross section. Exact uniformity of cross section is obtained by the process known as "flashing," in which the filaments are brought to incandescence with electric current while surrounded by gasoline vapor or some other gas, rich in carbon and readily decomposed by heat. As the filament is hotter at points of smaller diameter, the gas is decomposed faster and more carbon deposited on the filament surface at these points until perfect equality of cross section is attained, when the temperature becomes uniform. The deposit of carbon then proceeds equally along the entire length of the filament and is continued until the desired diameter is reached. After the flashing process, filaments of the better grades are "metallized" by subjecting them to the high temperature of the electric furnace, which so changes the surface carbon that it acquires metallic characteristics and can be operated at a much higher temperature than the crude carbon deposited in the flashing process. All filaments are cemented to two short lengths of platinum wire which in turn are soldered to two copper lead wires and sealed into a length of glass tubing (1—Figure 25), platinum being nec-

essary at the point where the circuit passes through glass, as this metal expands and contracts with heat changes at the same rate as glass and so maintains an air-tight seal through the widest variations of temperature. The glass tube bearing the filaments is now introduced into the globe or bulb, and the two welded together (at 3 — Figure 25), after which the bulb is exhausted through a small tube (2 — Figure 25) at its tip — the filament being heated to expel occluded gases as above. When the desired vacuum is reached the tube is sealed off with a blowpipe, and the lamp is then ready for mounting.

While this process of manufacture has been gradually growing more perfect, however, pure science has been gaining a clearer insight into the relations between the heat of a body and the light which it gives off; and now, when the carbon lamp can be produced at a lower cost and in more perfect form than even Edison dared hope, a new filament material, developed along the lines indicated by science, bids fair to monopolize the market. It has been known for many years that the higher the temperature of a body the higher the percentage that its light radiations bear to the radiations of heat, which inevitably dissipate the greater part of the energy consumed by any light source. Herein lay the fundamental reason for the use of the most

refractory of all substances, carbon, for an incandescent material. But recently, scientific investigations have shown that although carbon can be heated to a higher temperature than any other known substance before boiling or melting — a temperature of 3,700 degrees Centigrade — it unfortunately begins to evaporate at about 1,800 degrees Centigrade, so that this latter temperature is really the limit for carbon filament incandescence. Above this point the carbon rapidly vaporizes and deposits a black film over the inside of the globe. Knowing this, it at once became evident that some substance having a lower melting point than carbon might still be operated at a higher temperature if it chanced to have a higher evaporation point, and in working along these lines the rare metals, tantalum, osmium, tungsten, and others were tried successfully. Tungsten especially meets the requirements, as although it melts at 3,200 degrees Centigrade — 500 degrees lower than carbon — it does not begin to evaporate until raised nearly to the melting point and consequently can be operated at such a high temperature that it produces over twice as much light radiation for a given energy consumption as does the best carbon filament. At first the tungsten lamps were extremely fragile, for, in order to meet the standard 110-volt distribution pressure, the filament diameter in a 20-candlepower



Tungsten "wire type" lamp, showing lead wires (l), platinum wires through glass seal (p), filament support (s), and long, continuous wire filament (f)

lamp must be reduced to about 0.001 inch — less than one-fifth that of the corresponding carbon. Very recent improvements in the manufacture of the tungsten filaments, however, have been made, which give it a tensile strength four or five times as great as mild steel, and it will undoubtedly soon dominate the incandescent lighting field.

The extent and importance of this field is indicated by the 120,000,000 lamps in service in 1910, consuming $225,000,000 worth of electrical energy per year — a complete justification for the men who risked $40,000 in order that Edison might make one more attempt at the supposed impossibility — the production of a commercial incandescent light.

XII

THE ELECTRICAL REVOLUTION

"THERE they go! there they go! we have succeeded at last." On the table in the laboratory of the Royal Institution, September 3, 1821, stood a little apparatus very similar to that shown in Figure 26, consisting of a vertical glass tube closed at both ends by corks, and having a small amount of mercury in the lower end through which one pole of a bar magnet was thrust, while from the upper cork a stiff wire was loosely hung so that its lower end dipped in the mercury. Michael Faraday and his brother-in-law, George Barnard, had just completed the arrangement a moment before by connecting several voltaic cells to the circuit running through the hook supporting the stiff wire, thence along this wire to the mercury pool and then back to the battery. And now as Faraday exclaimed, "There they go," the lower end of the wire began to move slowly and jerkily round and round the magnet pole. Small wonder that Faraday "danced about the table with beaming face"— for there before them was the first electric motor, the mysterious

source of motion which was to be developed until to-day we have grown so accustomed to it in electric cars, in noiseless automobiles, and in the almost numberless applications of power motors, that we have nearly forgotten its mystery and only remember its wonderful usefulness.

Oersted had stated in 1819, almost immediately after his discovery of the deflection of a magnetic needle by the current in a wire, as discussed in the fourth chapter of this book, that "the electric conflict acts in a rotating manner"; for, said he, deflections of the needle in opposite directions are obtained when it is held first above and then below the current-carrying wire, and it is easiest to think of this as due to a force acting in a circle about the wire axis. But Oersted and his immediate followers soon forgot this brilliant statement of the truth and wasted their experiments on the assumed but purely fictitious attraction of the wire for the needle.

In 1820 Faraday was commissioned to write a history of electro-magnetism for a monthly periodical, and in his thorough-going way he repeated all the experiments made by others before attempting to describe them. He quickly assured himself that the force between the magnet and wire did not produce the slightest tendency to draw them together or push them apart, but rather to cause the north pole to rotate in one direction around the

wire while the south pole was urged to the opposite direction of rotation. In other words, a magnet pulled in opposite directions at its poles was merely set at right angles to the wire axis. The magnet as a whole then could not rotate, but if one pole could be obtained without the other, rotation should result. Eventually he found it easier to take advantage of Newton's law that action and reaction are equal, or to allow the wire to move while the magnet remained stationary, as in the apparatus of Figure 26, the arrangement of the device limiting the reaction of the current in the movable wire to one pole of the magnet. With this apparatus he verified his expectation that the direction of revolution could be reversed by reversing the direction of current flow, or by reversing the magnet but maintaining the current direction.

The relation of these different directions is best remembered by *Fleming's left-hand rule* (Figure 27), which states that if the thumb, forefinger and middle finger of the left hand are held so that each is at right angles to the other two, the forefinger pointing along the lines of force and the middle finger along the direction of current flow, then the thumb will point in the direction of motion. Applying this to Figure 26: if the north pole is above the mercury surface and the current flows down-

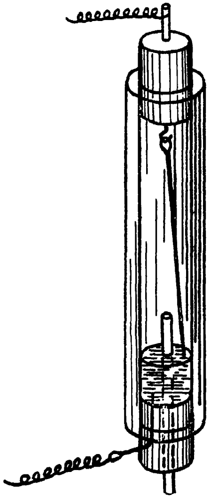


Fig. 26. Faraday's first device for showing the electrical revolution

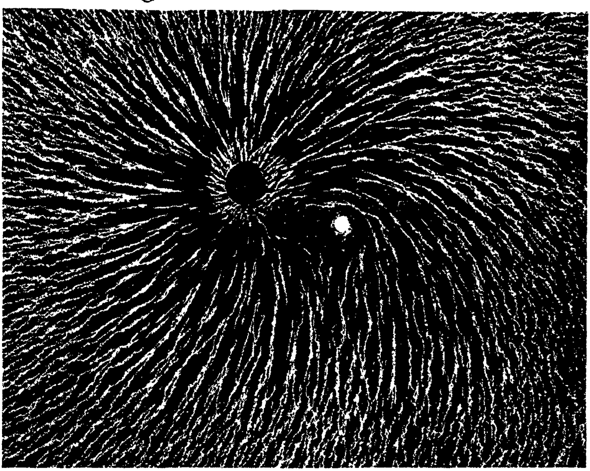


Fig. 28. Lines of force about a north magnetic pole (black circle), and a wire carrying current down through plane of paper (white circle)

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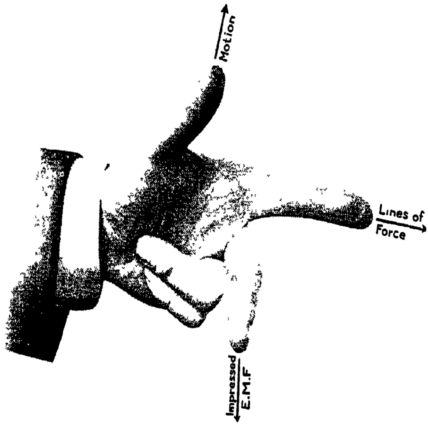


Fig. 27. Fleming's "left-hand rule" for finding the direction of motion of a conductor when the direction of the magnetic field and of the current flow are known [Page 132

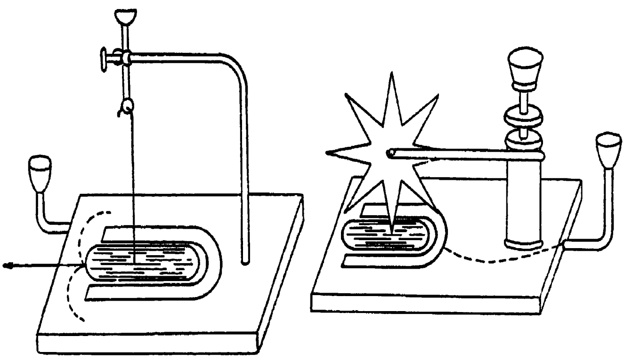


Fig. 29. (a) Rearrangement of Faraday's device using horseshoe magnet
(b) Barlow's wheel developed from (a) for securing continuous rotation [Page 134

ward along the wire, as the lines of force radiate *from* the pole like the spokes of a wheel, we find that the wire will rotate in a clockwise direction as we look down on the mercury surface.

But why does it rotate? We remember that according to Faraday's theory of lines of force (Chapter IV) these lines are in tension along their length and mutually repel each other. Does the current flowing in the wire call into play either this tension or repulsion and so cause rotation? In Figure 28 we have an iron-filing diagram of the lines of force about a north magnetic pole and a wire in which a current is flowing downward — the same conditions we assumed for Figure 26 — and here we can see how the tension, tending to pull the lines straight, forces the wire ahead; while if the diagram were perfect we should see that the lines above or behind the wires are crowded together, so that the mutual repulsion tends also to produce the clockwise movement. If no current were flowing in the wire the field would show uniform radial lines of force everywhere similar to those in the left-hand side of Figure 28 and the wire would remain at rest. Again, then, Faraday's conception of lines of forces enables us to picture the cause of electrical action. As in the generation of electric currents by induction, we saw that whenever a wire was moved through a field of force, or cut the lines, an

e. m. f. was induced, tending to cause a current to flow through the wire, so, in the production of motor action, we find that whenever a current flows at right angles to a field of force, or whenever the lines of force are distorted by a current, a mechanical pressure is produced tending to move the conducting wire.

Many of these conceptions, however, developed gradually in the fifty years following Faraday's discovery. At first the developments were simply modifications of his original device. A horseshoe magnet was substituted for the bar magnet and arranged as at A, Figure 29; and as the wire tended to rotate in one direction about the north pole, and in the opposite direction about the south, as shown by the dotted semicircles, the actual resultant motion was in the direction of the arrow. The wire, that is, was thrown out of the mercury and thus broke the circuit; then, of course, the action ceased and the wire fell back, this cycle being repeated as long as a battery was connected. In 1823, Barlow substituted the star wheel shown at B, Figure 29, in which a new point of the star entered the mercury just as the preceding point was pushed out, continuous rotation resulting.

And so on through forty years various applications of the original principle were made in the attempt to rival the steam engine with *electro-*

magnetic engines, as the motors were universally called. In 1838, Jacobi produced a motor-driven boat attaining a speed of four miles an hour. A few years later Professor Page of the Smithsonian Institution originated a design that has been preserved in the toy electric engines, so called, in which iron plungers are alternately pulled into solenoids arranged on opposite sides of a "walking beam" similar to those used in side wheel steamboats, the motion being transmitted through a crank to a heavy flywheel. This Page engine, installed on an electric car, even made a 10-mile trial-run from Bladensburg to Washington in two hours, and would have done better if one of the battery jars had not broken. Throughout the development, the limitations of the primary battery as a source of power were keenly felt. In 1857 the British Institute of Civil Engineers discussed with deep interest the possibility of producing a horsepower from less than 45 pounds of zinc and decided that until this could be done coal and the steam engine were the only practicable source of power.

It was, therefore, not until the development of engine-driven electric generators, which began about 1870, that the commercial use of motors was practicable, and several independent workers soon found that in developing this generator a much better form of motor had also been developed; for

the generator and motor proved to be the same machine, mechanical power being supplied in one case and electrical power produced, while in the other electrical power was supplied and mechanical power produced.

This can be made clear by considering Figure 30. With currents flowing as shown, Fleming's left-hand rule indicates that the reactions of both ends of the loop aid in producing rotation about the axis. As soon as the plane of the loop is at right angles to the lines of force which pass from the north to the south pole the tendency to rotate stops, for the push in opposite directions on the two wires is now in a straight line and merely tends to force the sides of the loop farther apart. If there is now sufficient momentum to carry the loop slightly beyond this position, called a *dead center*, the commutator reverses the direction of current flow through the loop, the push changes from an outward to an inward direction, and another half revolution is performed, so that by adding a flywheel a fairly uniform speed of rotation may be obtained.

Now suppose a second loop exactly similar to this is attached to the same axle at right angles to the first and connected to a separate commutator with brushes arranged in series with the first pair. Evidently, when the first loop is on a dead center the second is in a position where the push exerts

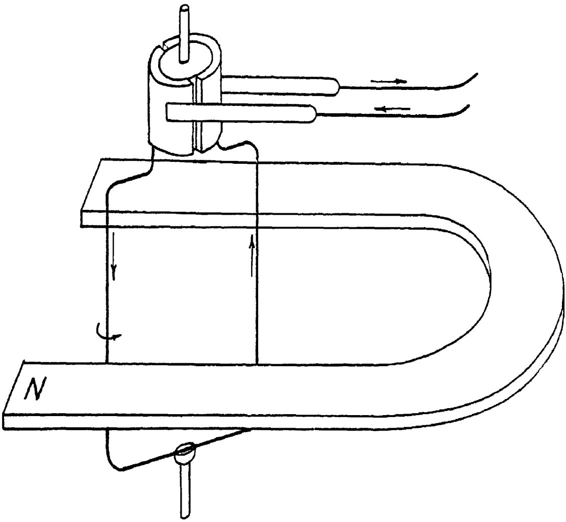
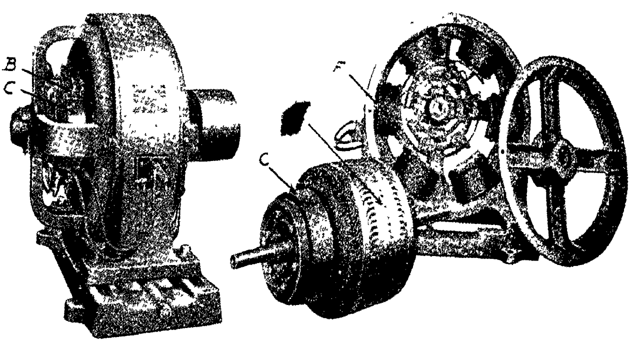


Fig. 30. Further development of Faraday's device showing evolution of modern motor armature



Six pole modern motor showing multi bar commutator at (c), brüshes at (b). Armature conductors or winding at (w) and at (f) field coils replacing permanent magnet of Fig. 30

the maximum tendency to rotation, or, in other words, the position of *maximum torque*, and with this arrangement the flywheel can be eliminated. By placing more and more loops at intermediate angles the turning tendency or torque can be made more and more uniform and stronger and stronger for all positions of the loops, and by placing an iron core within this hollow cylinder of loops the number of lines of force passing from the north to the south pole will be greatly increased. Careful experiments have shown that the push on a wire is equal to the strength of the current flowing multiplied by the strength of the field, so that the iron core again greatly increases the torque. But all these separate loops with separate commutators would make a very cumbrous machine and it was not until Siemens, Gramme, Edison, and a score of other pioneers developed schemes whereby these loops could be arranged in a continuous winding on the iron core (the winding having short connecting *taps* from properly spaced points to a single commutator with many bars) that the modern *armature* was realized. Returning to the simple loop of Figure 30, we see that as it rotates as a motor armature the conductors cut lines of force, and applying Fleming's right-hand rule (see Chapter V) we find that an e. m. f. is generated, tending to cause a current to flow in the direction opposite to the

motor current. If, then, we placed a pulley on the shaft and turned the loop mechanically it would generate currents; or, a motor is simply the reverse of a generator.

The e. m. f. generated in the motor armature by its motion — *the counter e. m. f.*, or *back e. m. f.*, as it is called (because it acts against the e. m. f. which is causing the rotation), has a very important bearing on the motor action. If an armature at rest is connected to a constant e. m. f., the current flowing through it is, in accordance with Ohm's law, equal to the applied e. m. f. divided by the armature resistance. But as the motor speeds up, the counter e. m. f. is generated and becomes greater and greater, thereby reducing the current through the armature more and more, until a speed is reached such that the impressed e. m. f. minus the counter e. m. f. forces a current through the armature resistance just sufficient to give the magnetic push required for turning the armature at that speed. If a load is put on the motor, the armature slows down and the counter e. m. f. decreases sufficiently to allow the current to increase to the amount required for the stronger push. By making the armature resistance very low a slight decrease in speed may give a large increase in current, so that the motor can be made to have nearly the same speed from no load to full load, or good

speed regulation. In this case, however, the current before the motor starts will be great enough to burn the commutator seriously, so it is necessary to use a variable resistance in series with the armature to limit the current until the armature speeds up, when this *starting resistance* is gradually removed or *cut out.*

Early in the development of motors and generators the permanent field magnets were replaced with electro-magnets giving stronger and readily controlled magnetic fields. In *series machines* the current passes through the field winding and thence through the armature, and in consequence a series motor can exert a very heavy pull at starting, as the rush of current through the armature at rest gives a very strong field. Series motors are, therefore, used for electric cars and similar service. In *shunt machines,* on the other hand, the field is connected in parallel with the armature, and its strength depends only upon the impressed e. m. f. Shunt motors, therefore, exert lower starting torque but have very constant speed regulation. Combinations of the two methods of field connections are also made; and in alternating current motors further phenomena are encountered, giving a wide range of characteristics adaptable to almost every class of service.

This wonderful adaptability of the motor, its

remarkable speed control, its cleanliness, reliability, and efficiency, the range of sizes in which it can be made from the tiny fan and sewing machine motors to the 6600 H. P. giants used in the steel mills, and the ease with which power can be transmitted to it from great distances, have gone far to reverse the relation between steam and electricity, so much deplored by the scientists of '57, and so have given to Faraday's "electro-magnetic rotations" or "electrical revolutions" a fundamental share in the marvelous industrial advance of the last thirty years, which in quite a different sense and with even larger truth is generally accredited to The Electrical Revolution.

XIII

A BLACKSMITH AND HIS DREAM

SOMETIME about 1834, Thomas Davenport of Brandon, Vermont, wearied of the routine of horseshoeing and wagon repairs which his reputation of "good blacksmith" brought him, and saw visions of a new form of transportation which should make horseshoeing forever unnecessary. The news of Faraday's discovery of electrical rotation and descriptions of crude forms of motors were just beginning to attract general attention, and to Davenport came the idea of applying the motor to the propulsion of a vehicle or car. By 1835 he had developed a working model running on a circular track a few feet in circumference, and held a public exhibition in Springfield, Massachusetts, and later in Boston.

He became so interested, indeed, in the possibilities of electric motors that he designed over a hundred operative forms during the next six years, applied them to printing presses and other machines, and finally secured from the Patent Office a grant of a claim for "Applying magnetic and

electro-magnetic power as a moving principle for machinery, or in any substantially the same principle."

Apparently he was completely equipped as the successful pioneer in electric traction, but — he was just fifty years ahead of his neighbors. To them his railway was only an interesting toy, and the circular track and the first electric car were, like their inventor, forgotten. Some sixty years later, after the electric railway had been successfully developed by other men, the model was found and the details of Davenport's career unearthed — but the fundamental patent had long expired.

It is noteworthy that in Davenport's railway the rails were used to conduct current to the motor, one rail being positive and the other negative; the wheels on one side of the car were insulated from those on the opposite side and the motor was connected to wires making contact with these wheels. Other early railways were almost all based on the attempt to carry a primary battery in the car. The first of these self-contained electric locomotives was made by a Scotchman, Robert Davidson, in 1838, and in a trial run on the Edinburgh and Glasgow Railway attained a speed of four miles an hour. Then came Professor Page's 1851 car, which we noticed in the last chapter, and several other similar cars, all doomed to failure through dependence on

the expensive and unreliable production of energy by the battery.

But the idea of transmitting the electric power from a central stationary point to the moving car, as at first contemplated by Davenport, was gaining adherents. The use of the rails as conductors was patented in England in 1840; in 1855 an English patent was issued for the use of an overhead conductor, the trolley wire of today; and then for twenty years all progress ceased — the electric battery could not compete with steam. No sooner, however, was the steam-driven electric generator developed than the possibilities of the lighter equipment, more frequent stops, and smokeless operation of electric cars began again to attract pioneers in all parts of the world.

In 1875, a poor mechanic, George F. Green, built a model railway at Kalamazoo, Michigan, which he operated by a battery; but he abandoned it when he found that he could not construct the dynamo he realized was necessary for commercial success. In 1879, at the Berlin Exposition, the firm of Siemens & Halske constructed a road one-fourth mile in length on which a small locomotive drew three cars, carrying about twenty people. The power was transmitted from a Siemens dynamo through a single insulated rail laid between the track rails to another similar dynamo mounted on

the locomotive to serve as a motor, thus early exemplifying the present *third rail system.*

Simultaneously in this country, fundamental advances were made by Stephen D. Field and Edison. Indeed, in the words of Frank J. Sprague, himself one of the greatest pioneers in the electric railway field, "Edison was perhaps nearer than any other on the verge of great possibilities, had it not been that he was intensely absorbed in the development of the electric light." As a part of his work on the light and its applications, Edison had succeeded in so improving the dynamo as to raise the efficiency of converting mechanical to electrical power from about 40% to nearly 90%; and although his claims were declared absurd by most electrical men, who asserted that 50% could be shown mathematically to be the highest possible efficiency, he had such faith in these claims that he took time in the midst of his work in electric lighting in the spring of 1880 to superintend the building of an experimental road about one-third of a mile long, near his laboratory at Menlo Park. On this road he hoped to demonstrate the results attainable with dynamos of 90% efficiency, used both as generators and motors. And he did.

As can be seen from Figure 31, a locomotive was used to draw three cars on a track of light rails laid more or less haphazard without ballast. At one

Fig. 31. Edison experimental railway at Menlo Park, 1880

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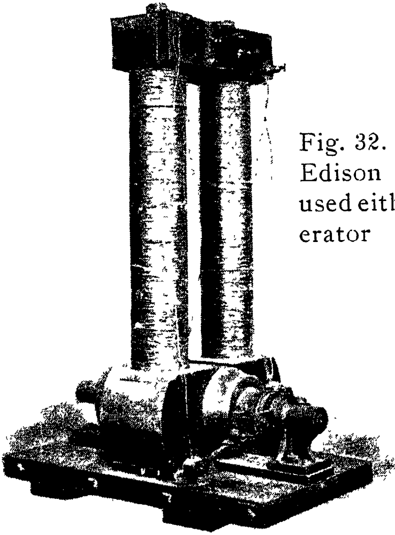
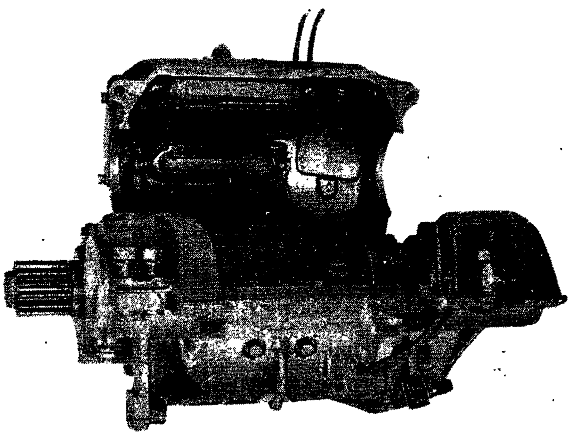


Fig. 32. Original Edison dynamo used either as generator or motor



Modern G. E. "Split-frame" 40 h. p. railway motor used in both 2 and 4-motor equipments, giving each car a maximum of 80-160 h. p.

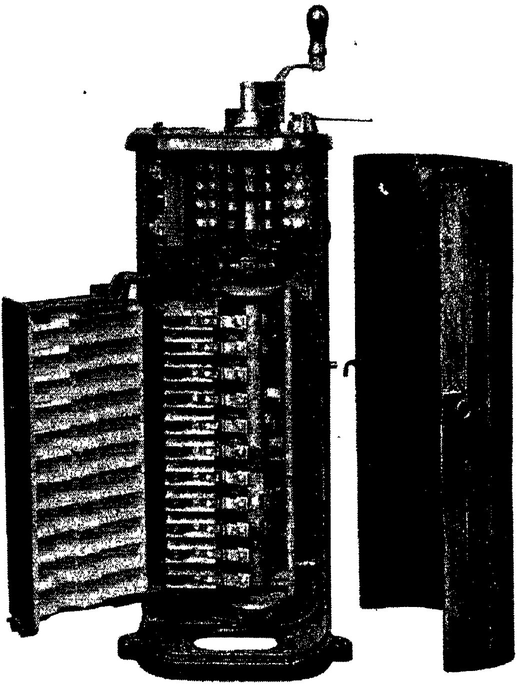
point of the road a drop of 60 feet occurred in a distance of 300 feet, and the curves were of startlingly short radius, but after a year of work, speeds of 40 miles an hour were obtained. The locomotive consisted simply of one of Edison's regular 12 H. P. generators (Figure 32) mounted on its side on the platform and connected to the axle of the truck through friction gears, later replaced by belts and pulleys. The wheels were insulated from the axle and the rails used to form the electric circuit, just as in Davenport's model, the rails being insulated from each other by interposing tar canvas-paper between them and the ties.

At first the motor was connected directly to the circuit to start, but this was found to jolt the apparatus so severely that *resistance boxes*, or frames carrying coils of high resistance wire, were introduced into the circuit to reduce the starting current, and were then gradually short-circuited and so removed as the motor speeded up and its counter e. m. f. became sufficient to limit the current to the normal value. Many accidents occurred on the flimsy track, and much equipment was demolished. But commercial electric locomotive operation was well in sight when Edison's patent applications were declared in interference with those of Stephen Field and after long negotiations the patents of both were bought by "The Electric

Railway Company of America"; the work of development was assigned to Field, and Edison turned his attention to other matters.

The Electric Railway Company exhibited an electric locomotive named "The Judge," in Chicago in 1883, which hauled nearly 25,000 persons in an attached passenger car during the two and a half weeks of the Chicago Railway Exposition. "The Judge" did good service also in awakening public interest at other expositions, but aside from this the work of Edison and Field hardly exercised the influence which it deserved.

Indeed, the first commercial railway had already been installed at Lichterfeld, Germany, in 1881; but the real beginning of the modern development is generally credited to the United States and to Sprague in recognition of his work in building the system at Richmond, Virginia. For in place of the one- or two-car roads previously operated, the Richmond contract, started in the spring of 1887, included "the building of a generating station, erection of overhead lines, and the equipment of forty cars, each with two 7½ H. P. motors on plans largely new and untried." In this system the e. m. f. employed was raised to 450 volts, the trolley wire being maintained at this pressure above the track rails, which were used as the return circuit.



G. E. type k-36-f controller, showing drum and contact fingers for accelerating car from standstill to maximum speed, using "series parallel" system of control [Page 149

The importance of this increase in pressure is easily seen. It will be remembered that we found, in considering the heat generated by the electric current, that any current in flowing through a resistance wastes energy as heat at a rate equal to the square of the current in amperes multiplied by the resistance in ohms. We also found that the rate of electric energy supply is measured by the product of the current and the pressure at which it is supplied. Thus a 10 H. P. motor uses energy at the rate of 7,460 watts; and this rate at 74.6 volts means a current of 100 amperes; while at 746 volts only 10 amperes will be required. If now the current must flow through a circuit having 1 ohm resistance, 100x100x1 or 10,000 watts will be lost as heat if power is delivered at 74.6 volts, while only 10x10x1 or 100 watts will be lost if power is delivered at 746 volts. That is, the transmission loss decreases as the square of the increase in voltage; and by raising the trolley pressure from 100 volts to 450 volts, and later to 600 volts — the present standard — Sprague decreased the transmission loss to 5% and then to 3% of its amount in the early 100-volt railways.

But the loss was still too high and the only safe means to get further reduction was to lessen the resistance of the circuit by using larger conductors. As the size of trolley wire which can be

conveniently suspended by *brackets* or *span wires* was comparatively small, Sprague adopted a system of large feeders carried on the poles or underground, and cross connected to the trolley wire at frequent intervals. This made the trolley practically one strand of the large feeder cable and the resistance of the trolley circuit could easily be reduced. In spite of the great gain from using feeders, however, the loss was still too large, for the resistance of the trolley was, of course, only a part of that of the entire circuit. The rail return was found to have such a high resistance at certain joints that the return current left the track and flowed along parallel water and gas pipes, leading not only to high transmission losses but to electrolysis, gradually destroying the pipes and rails just as it gradually consumes the electrode of an electro-plating cell.

Efforts were at once begun to lower the resistance of the track by connecting the successive rails by heavy copper wires at each joint and these wires or *bonds* have gradually been increased in size and perfected in connection, until today the bonded joints have lower resistance than an equal length of rail. In the best construction, indeed, the question of bonds is so important and so expensive that it is found cheaper to weld the rail into one continuous length with electrically generated heat

and to reduce its resistance further by running heavy copper *ground return* cables or *negative feeders* connected to the rail at convenient points.

The method of starting and controlling the motors in the Richmond cars also contained great improvements; for although the principles of the "series-parallel" control had been outlined by Dr. Hopkinson in 1881, Sprague worked out the practical problems. With this system the armatures of the two motors are connected at starting in series with one another and with a resistance which is reduced by steps as the car speeds up until the motors are in series directly across the full *line pressure,* each thus receiving one-half of this pressure and so giving the car about half its maximum speed. Each motor is next connected to the line separately in series with a resistance, and the two resistances are reduced together step by step until each motor receives the line pressure, the two motors thus being in parallel, and the maximum speed is obtained. These complicated changes are made by a switching arrangement called a *controller,* in which a drum carrying several connecting segments, and rotated by the motorman through a crank handle, completes the circuit as desired between various spring contacts.

The motors in the Richmond system, too, were carried on the trucks and geared to the axles as in

the latest cars, and although many minor improvements were required the essentials were well in hand.

The development since 1887 is almost inconceivable. At the beginning of that year there were less than forty miles of electric railways and not more than forty cars in the United States. Ten years later about 20,000 miles of track were equipped, and 50,000 cars were in service, representing an investment of one and a half million dollars; and today the industry is capitalized at over $4,000,000,000.

But to his neighbors Davenport seemed always a dreamer.

XIV

THE MYSTERY OF THE IRON BOX

VERY early in the commercial development of electric lighting, following Edison's successful manufacture of the bamboo incandescent lamp, the limitations of a 110-volt transmission pressure began to be felt. As we have seen in considering the electric railway, the loss of power as heat in the line conductors increases as the square of the current, and any considerable power at 110-volt pressure means a current so large that it can be transmitted economically for only very short distances. The current corresponding to a given power can be decreased to any desired extent, of course, by proportionately increasing the line pressure, as power is equal to the product of volts and amperes, but in the case of the incandescent lamp the pressure was fixed at 110 volts. Efficient filaments became too fragile for satisfactory service if made for high pressures, and thus the problem was reduced at once to finding some way of transmitting power to the consumer at a fairly high voltage and then changing this pressure to 110 volts before it was applied to the lamps.

One method available was evidently to generate D. C. current at, say, 550 volts and transmit at this pressure to the user's premises, where a 550-volt motor should be installed to drive a 110-volt generator. But rotating machines were expensive and required constant attention, and hence this scheme was feasible for large consumers only. Very soon, too, demand for power began to arise at such considerable distances from the central station that even 550 volts was too low for economy, and great difficulties were experienced in building D. C. machines which would successfully generate higher pressures. The direct current commutator especially became a well-nigh insurmountable obstacle when the pressure between adjacent segments was raised above a few volts, and, although a number of systems were built and operated by using several D. C. generators connected in series — notably one at Brescia, transmitting 700 horsepower twelve miles at 15,000 volts — the plan was much too complicated and costly for American urban practice. In the meantime, however, alternating currents were beginning to be investigated and, through the work of William Stanley in 1885, at Great Barrington, Mass., soon came to dominate the field wherever transmission to a considerable distance was required.

To understand Stanley's work it is necessary to

review the action of an alternating current generator of the simple form shown in Figure 33. If the conducting loop represented by the heavy line is rotated in a clockwise direction, current will flow during the first half-revolution (see Fleming's right-hand rule, page 63) from the inner to the outer collecting ring through the loop and thence from the outer ring through the external circuit and then back to the inner ring. During the second half-revolution the flow will be from the inner to the outer ring through the external circuit, and so on, reversing in direction every half-revolution. At any particular instant the strength of the current in a straight connecting conductor is proportional to the generated e. m. f., in accordance with Ohm's law, and this e. m. f. is in turn proportional, as we know, to the rate at which lines of force cut or are cut by the conductor. Thus at the instant shown by the heavy line drawing of the loop, the two sides are moving practically parallel to the lines of force, so that no cutting occurs, and hence no e. m. f. is generated; while as uniform rotation continues the conductor cuts more and more lines for each degree added to the angle of motion until it reaches the position shown by the dotted loop, where the rate of cutting and therefore the induced e. m. f. is at a maximum. Continuing the rotation the e. m. f. decreases until at

the end of a half-revolution from the initial position it is again zero, whence it continues to decrease or (what is really the same thing) begins to increase to a maximum again in the opposite direction.

The successive changes in the value of the e. m. f. are best shown by a curve similar to that in Figure 34, where the passage of time is represented by increasing distance from the vertical line at the left along the central horizontal line or axis, and the magnitude of the induced e. m. f. at any instant by the height of the curve above or below this axis. Figure 34 thus indicates a pressure increasing from 0 volts to a positive maximum, and decreasing to zero in 1/50 of a second, then decreasing further to a negative maximum, and so back to 0, having passed through the complete sequence or *cycle* of values in 1/25 of a second. *Twenty-five cycles* of pressure per second will thus be produced as long as the generator continues to revolve at normal speed, or, as it is generally stated, the *frequency* is 25 cycles. The figure is reproduced from a photographic record of the instantaneous cyclic variation in the pressure of the Commonwealth Edison Co.'s 25-Cycle System, the complete curve from the vertical line to the point marked 2/50 being frequently called the *wave form* of the system — a term which has no rela-

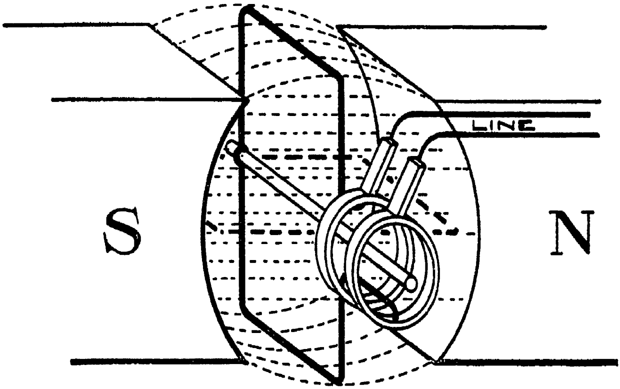


Fig. 33. Simple alternating current generator

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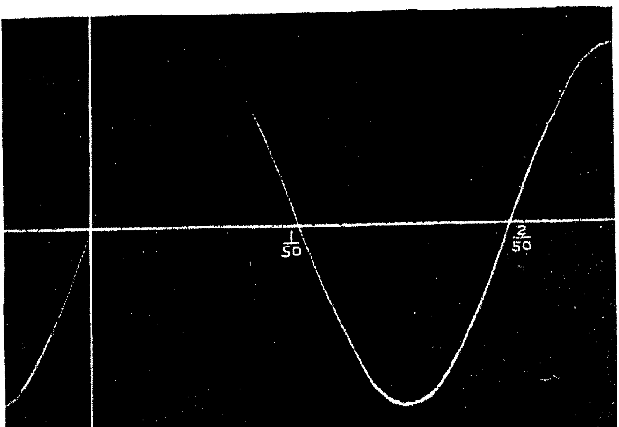

Fig. 34. Alternating pressure wave form of Commonwealth Edison Company's 25-cycle system

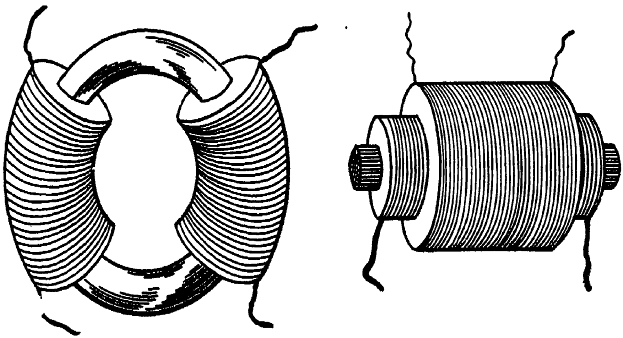

Fig. 35. (a) Simple transformer developed from Faraday's anchor ring
(b) Induction coil type of transformer
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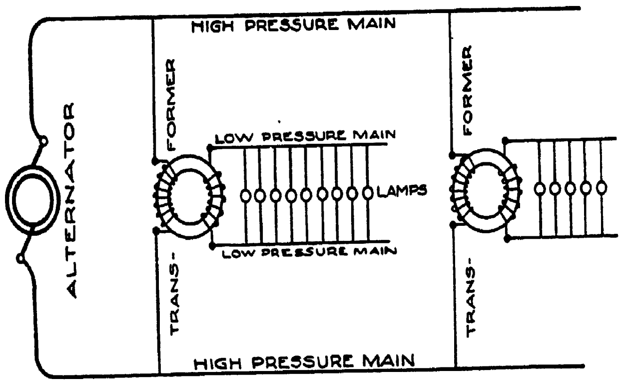


Fig. 36. Elementary A. C. circuit showing two transformers connected in parallel to high tension line and supplying customers with 9 and 5 lamps respectively [Page 157

tion, however, to the electric waves used in wireless telegraphy.

Such an alternating pressure applied to the terminals of an incandescent lamp produces a current varying just as the voltage varies, or having just the same wave form, and it has been found that heat is produced thereby at the same rate as by a direct curent 0.7 as great as the maximum value of the alternating current. The *effective value* of an alternating current is thus said to be 0.7 of its maximum value. This relation varies with the wave form, and in some circuits the current wave form is very different from the wave form of the pressure causing it to flow; indeed alternating currents introduce many questions too complex for the present discussion. But it should be fairly clear from the above that any given alternating current has a continuously changing instantaneous value, and that the effect of the recurring series of instantaneous values in producing heat or doing other work is exactly equivalent to some direct current value which can be calculated.

In our consideration of Faraday's discovery of the induced currents in his anchor ring (see Chapter V) we found that the only condition which must be fulfilled in order that induced currents should be produced in one of the coils of wire wound on the ring (as for example, the right-hand coil of A,

Figure 35) was, that the value of the current should be changing in the other coil — in the left-hand winding of A. Using direct currents this occurs only when the circuit through the left-hand coil is made or broken, for then the lines of force threading the second coil increase or decrease and so induce e. m. f.'s by cutting the turns of the winding.

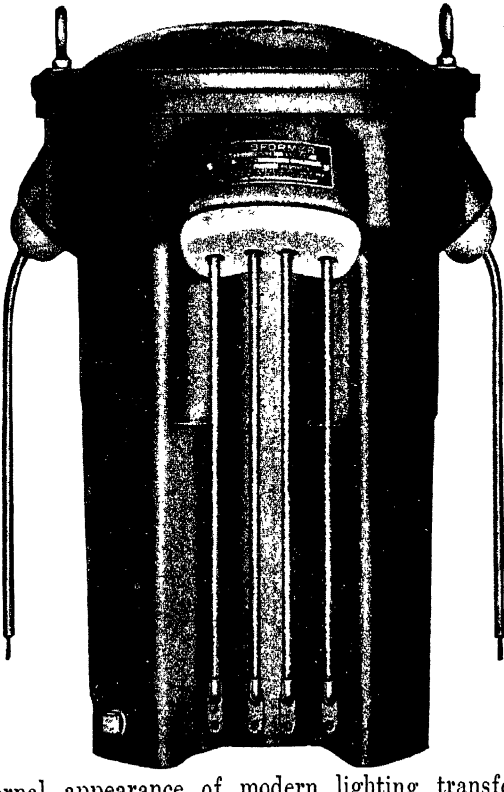
Suppose now, however, we cause an alternating current to flow through the *exciting* or *primary coil.* As the current value changes continuously, the magnetism — the number of lines of force — in the iron ring or *core* will also change, passing through a regular cycle of values, and now an alternating e. m. f. will be induced continuously in the second coil or *secondary* winding. But the value of the e. m. f. induced, as in all other cases, depends entirely on the number of lines of force cut per second, and since 10 lines cutting one turn generates the same e. m. f. as one line cutting 10 turns, we can get any pressure desired by altering the number of times the secondary is wound round the core, or the number of *secondary turns.* Thus if we require a pressure of 100 volts and we find that with a given primary and core a secondary of 10 turns gives a pressure of one volt, the winding must evidently be increased 100 times or to 1,000 secondary turns.

Here then is the solution of the transmission problem. The first attempt to apply it commercially was made in England in 1883 by Gaulard and Gibbs, using a modified form of induction coil similar to B, Figure 35, and the attempt was sufficiently promising to excite interest. But the real solution was reserved for Stanley, who first conceived the idea of the alternating circuit shown in Figure 36, prototype of all present-day alternating current or *A. C.* transmissions.

Working in an abandoned rubber-mill in 1885, he built about a dozen transformers, or, as he then called them, "converters," to reduce the primary pressure of 500 volts to 100-volt secondary pressure — each transformer of sufficient current capacity to supply twenty-five 16-candlepower lamps, and installed his system in one or two stores and the hotel at Great Barrington. The primary coil connected directly across 500 volts had a resistance of only one ohm, and electricians familiar with Ohm's law and with direct current circuits expected some 500 amperes to flow through each primary, burning up the transformers and wrecking the generator. Nothing of the kind happened and the foreboders were quite ready to abandon all theories forever when they found that with the lamps turned off, or, in other words, when the secondary was on open circuit, the actual current flow was less than two am-

peres, while as lamp by lamp was switched on in the secondary circuit the primary current increased proportionately, one ampere in the secondary corresponding to 1/5 ampere in the primary. Where was the discrepancy — what was wrong with Ohm's law?

The explanation was soon found and is really very simple. Just as, in the case of a motor, an e. m. f. which opposes the flow of current is induced in the armature by motion through the magnetic field, so in the primary coil the variation of the field strength, equivalent to movement of the magnetic lines past the coils, induces an *e. m. f.* in the primary simultaneously with the induction in the secondary winding. In the primary this *back e. m. f.* is in a direction opposed to the flow of current and of such a value that the difference between the applied and the back e. m. f. is just sufficient to cause a current to flow large enough to produce the magnetic field necessary to generate the back e. m. f. In other words, the obstruction to the flow of an alternating current through a wire wound around an iron core is much greater than to the flow of a direct current, being composed of a magnetic reaction, called the *reactance* of the circuit, as well as of the resistance of the conducting path. As current is allowed to flow through the secondary winding of the transformer by connect-



External appearance of modern lighting transformer manufactured by General Electric Company

ing lamp filaments or other conductors across the secondary terminals, the effect is as if a second magnetic field were produced of such magnitude and direction as to decrease the primary back e. m. f. sufficiently to allow a proportionate increase in the primary current.

In the transformers now used the primary current with the secondary open-circuited is so small, and the power lost in the transformer in heating the windings and magnetizing the core so trifling, that the relation — primary pressure × primary current = secondary pressure × secondary current — is very closely maintained. Hence, if the primary pressure is five times the secondary as in the original transformers, the current in the primary will be only 1/5 that in the secondary. To-day the most usual transmission pressure in cities is 2,200 volts, and the line currents are thus reduced to 1/20 of the value at 110 volts, or the losses are only 1/400 of those in the original Edison System. Moreover, these tremendous economies are obtained with absolute safety, for Stanley's designs have been modified and improved until the primary and secondary windings are so perfectly insulated from each other and from the core as to withstand five times the highest electrical pressure to which they are ever subjected.

Everywhere in our cities are to be seen poles

bearing mysterious iron boxes or tanks, in which two simple coils of copper wire interlinked with an iron core are immersed in highly insulating oil. In stations and sub-stations are to be found similar though much larger tanks containing larger units of the same design. No noise, no motion, no attention required, a toll of perhaps 2% taken from the power transformed when working at full load, but no limitation in size from one to 10,000 horsepower, and no limitation in safe transmission pressure from 1,000 to 140,000 volts — such is the modern transformer, direct descendant of the anchor ring of Faraday, applied and commercialized by William Stanley.

XV

THE SPIRIT OF ELECTRICITY

IN the preceding chapters we have briefly reviewed some of the discoveries of the great pioneers of the past and have followed the development of electric power and its gradual application to the production of motion, heat, and chemical changes. What of the pioneers of the immediate present and of the fast-approaching future? What new electrical service is to be found? What improvements in the old services are to be made, within our own times?

One of the most pressing problems of the world today is the production of some form of fertilizer to replace the rapidly diminishing store of Chili saltpeter, on which the entire food supply of mankind depends. Each crop abstracts nitrogen from the soil in large proportion; and unless that nitrogen is replaced, the earth must become sterile and barren. Heretofore this nitrogen has been replenished almost entirely from the deposits of the natural fertilizer, sodium nitrate or saltpeter, which have accumulated through the ages in a strip of

land between the Andes and the coast ranges of Chili. But this supply will be exhausted in fifteen years, and we must then begin to draw on the limitless reservoir of nitrogen in the atmosphere. A limitless reservoir! Then wherein lies any problem? Just here. The nitrogen in the air is a free gas, and in this state is lifeless and without effect on other substances; but nitrogen combined or *fixed* with the metal sodium and the gas oxygen, as in Chili saltpeter, is for some reason one of the most active of substances. Nitrogen gas pumped into the soil in large quantities influences growth not at all, but the nitrogen of a small amount of Chili saltpeter mixed with the same soil will increase the crops many fold. Fixed nitrogen, then, we must have, and for many years chemists have been striving to produce it. But the same lifelessness that makes the uncombined gas worthless as a fertilizer makes well-nigh impossible the task of uniting it with other substances. It appears that in electricity lies the only means of solving the problem.

As long ago as 1790 Cavendish found that a small amount of nitrogen was combined with water vapor to form nitric acid in the air through which an electric spark had passed, and later investigators found similar traces of this combination in the atmosphere after a thunder shower. The application of these discoveries, however, was made only a few

years ago by Messrs. Bradley and Lovejoy, who began experiments at Niagara. They used an apparatus giving some 400,000 electric sparks per minute in a cylinder through which large quantities of air, with its 80 per cent content of nitrogen, could be forced. The outgoing air contained 2 per cent of fixed nitrogen which could be used in chemical reactions to produce any of the nitrogen compounds desired.

In Norway, where electric power is even cheaper than at Niagara, there are being developed methods in which the air is passed through huge electric arcs with flames nearly a yard in diameter, and, although the direct production of fixed nitrogen from the electric spark or arc is by no means a finished process, it is certainly only a question of a few years before this new activity of electricity will be one of its greatest services. Meanwhile, Dr. Frank of Charlottenburg has discovered a means of causing calcium carbide, familiar as the source of acetylene gas, to combine with nitrogen when reheated in improved forms of electric furnaces, and the compound proves to be an excellent fertilizer. This distinctly electrical product will be used until the direct process is perfected; and so, in one form or another, electricity is fast becoming essential to the maintenance of world life.

The coöperation of electrical and chemical pio-

neers will also be required in improving the efficiency of light-production; and to understand how this is to be brought about it is necessary to consider for a moment just what light is. As the temperature of a body is raised, it begins to send out disturbances in all directions at perfectly definite intervals, new disturbances at shorter and shorter intervals being given off as the body or *radiator* gets hotter and hotter. When the temperature is sufficiently high to cause a part of the disturbances or *waves* to occur 400 millions of millions of times per second, these inconceivably rapid waves striking our eyes make us see the radiator as a dull red. As faster and faster waves are produced the red color becomes lighter, changes to orange, to yellow, and finally to a light white. But, although the temperature is rising, the slower disturbances — the waves which generate heat when they strike any body — are still being sent out at the old rate, and a large part of the work done on the body to raise its temperature to incandescence is thus wasted in heating the air or surrounding bodies. Fortunately, the higher the temperature of the body, the greater the percentage of work which is turned into useful light waves; and if we could get a lamp filament at the temperature of the sun, about one-third of the electrical work done on it would reappear as light.

This means, however, that the filament must withstand a temperature of 5,000° to 6,000° Centigrade (9,000° to 10,800° Fahrenheit), and carbon, the most refractory known substance, melts at 3,700° C.! Even this temperature cannot be reached, except in the arc lamp, for as we found in considering the development of the incandescent lamp (Chapter XI) carbon begins to evaporate at 1,800° C.; and so the limiting temperature for filaments today is just below the melting point of the metal tungsten, 3,200° C. At this temperature only one-fortieth of the electrical energy supplied is converted into useful light! Is there some other substance with higher melting point? and how shall we proceed to find it? All known elements fall into groups according to their various properties, and frequently the discovery of a new element has rewarded the search for that substance which should have the properties required to fill a gap in some otherwise closely related group. Such a gap still exists among the metals between tungsten and osmium (one of the first substances used for metal filaments), and the element to fill this gap will have a higher melting point than any known substance except carbon. The search for this material forms a very real part of present-day pioneering; and, when it is found, light production by incandescent lamps will probably have

reached its greatest efficiency. It is just possible, of course, that chemists may produce compounds of carbon with other elements which will have even higher melting points; but while this may be hoped, it now appears hardly probable.

Are we then to accept a 3 per cent yield as the maximum attainable in the generation of light—three watts out of every 100 converted into the light desired, the remaining ninety-seven going to produce the invisible and useless heat waves? True, this is a considerably better result than can be attained in any of the older forms of illuminants—but it certainly will not satisfy the coming generations whose slogan is to be "efficiency." Even now the way is dimly seen, and considerable advances have been made. In the *flaming arc lamps* dependence is no longer placed on the incandescence of a solid, but the carbons used are first impregnated with certain salts of calcium or other substances, which pass into vapor in the electric arc and there become brilliantly luminous, throwing out light waves far in excess of the amount corresponding to the temperature, so that 10 per cent or even more of the entire electric energy is converted into light.

This suggests that electricity in some way is directly causing the disturbances which we know as light; and, further, that if we could say just what

these disturbances are and just what electricity is efficient light production could be easily accomplished. Here we are back to the question with which we began this book — what is electricity? — and in the answer is to be found not only the solution of the problem of light, but the way to applications of electricity as yet hardly dreamed of. For the last thirty years the nature of electricity has been popularly considered the greatest of mysteries, but even in 1880 it was surely no more mysterious than gravitation, the force which keeps us from flying off the earth as water drops fly from a swiftly revolving wagon wheel; no more unknown than cohesion, the force which holds the particles of this paper or of any other matter together; no more uncanny, indeed, than matter itself. For is not matter so mysterious that even the denial of its existence forms part of certain philosophies and creeds? It is only because electricity is newly come into our fields of knowledge, and so still has clinging to it the atmosphere of the great unknown, that we feel its mystery, a mystery which today is fast passing as a conception of the substance of electricity comes almost within our grasp.

As early as 1873, Clerk Maxwell, the great Scotch mathematical physicist, calculated that an electric charge vibrating back and forth on a conducting body, or indeed, a charged body vibrating

mechanically, would send out disturbances which would travel at the known speed of light, 186,000 miles per second. This could only mean that light waves were produced by rapidly vibrating electric charges; and though the demonstration was purely theoretical it so well accounted for many of the known facts of light and electricity that *the electro-magnetic theory of light*, as it is called, was generally accepted. Since that time Herz and others have discovered ways of producing and controlling vibrating electric charges and of detecting and measuring the speed of the disturbances sent out. This speed has been found experimentally to be that of light, and now these electric waves are the almost commonplace means of transmitting the signals of wireless telegraphy. The disturbances which are easily recognized as electric waves are much slower than those perceived as light, occurring indeed only a few millions of times per second, but the identity of the speed of transmission goes far to verify Maxwell's theory. Now, a vibrating electric charge is equivalent to an alternating electric current; and, as we know, any current is affected by a magnetic field. If the theory is true, therefore, there should be some effect of such a field on the movements of the light-producing charge. This effect was actually discovered with the most refined optical instruments by Zeeman. It consists

in a slight change in the frequency of vibration of the light-giving body, a tiny shift in the color of the light which is sent out. Furthermore, from the measured amount of this change in color, Larmor, Lorentz, and others were able to compute the relation of the amount of charge to the amount of matter in the vibrating body, and thus to find that either the charge was comparatively very great or the body of matter almost infinitely small.

Simultaneously another line of experiment was being followed by Sir William Crookes and others, using sealed glass tubes exhausted to a high vacuum and provided with two electrodes extending through the glass. When a considerable pressure was applied to the electrodes a discharge from the negative electrode took place, which had the appearance of a column of luminous gas. This discharge could be deflected by a magnet, would cause a tiny paddle wheel to revolve when properly supported in its path, would cause certain substances against which it struck to phosphoresce, if suddenly stopped would produce the Roentgen or X rays, and in other ways behaved like a stream of tiny bullets, each carrying an electric charge. Long and careful experiments showed this to be substantially true; showed the discharge, that is, to be composed of flying charged particles, and these were found later to have the same ratio of electric charge to amount

of carrying matter which had been computed for the Zeeman experiments.

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these infinitesimal electrons from atom to atom; that an electric current in a liquid means a constant procession of atoms called *ions*, from each of which a single negative electron has been detached and the electrical equilibrium thereby destroyed; and that energy is transmitted electrically by the strains and stresses in the medium through which these electrons pass. This may seem vague, but our knowledge is still vague — the nature of electricity is almost known, but no one can say how long it will take to eliminate that "almost." Many physicists believe that, when it *is* known, gravitation, cohesion, matter, and many other outstanding problems will be problems no longer.

Looking back over the century and a half since Franklin flew his kite, noting the splendid achievements of the devoted pioneers, and realizing the service of electricity, it is but natural to regard our day as that of the full-grown manhood of the electric age — but the real electric age is to come; the probabilities of the future offer far greater prizes than the discovery of a new continent or the settling of an untilled land; and to the pioneers of this and future generations beckons the spirit of electricity.

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XV

THE SPIRIT OF ELECTRICITY

IN the preceding chapters we have briefly reviewed some of the discoveries of the great pioneers of the past and have followed the development of electric power and its gradual application to the production of motion, heat, and chemical changes. What of the pioneers of the immediate present and of the fast-approaching future? What new electrical service is to be found? What improvements in the old services are to be made, within our own times?

One of the most pressing problems of the world today is the production of some form of fertilizer to replace the rapidly diminishing store of Chili saltpeter, on which the entire food supply of mankind depends. Each crop abstracts nitrogen from the soil in large proportion; and unless that nitrogen is replaced, the earth must become sterile and barren. Heretofore this nitrogen has been replenished almost entirely from the deposits of the natural fertilizer, sodium nitrate or saltpeter, which have accumulated through the ages in a strip of

land between the Andes and the coast ranges of Chili. But this supply will be exhausted in fifteen years, and we must then begin to draw on the limitless reservoir of nitrogen in the atmosphere. A limitless reservoir! Then wherein lies any problem? Just here. The nitrogen in the air is a free gas, and in this state is lifeless and without effect on other substances; but nitrogen combined or *fixed* with the metal sodium and the gas oxygen, as in Chili saltpeter, is for some reason one of the most active of substances. Nitrogen gas pumped into the soil in large quantities influences growth not at all, but the nitrogen of a small amount of Chili saltpeter mixed with the same soil will increase the crops many fold. Fixed nitrogen, then, we must have, and for many years chemists have been striving to produce it. But the same lifelessness that makes the uncombined gas worthless as a fertilizer makes well-nigh impossible the task of uniting it with other substances. It appears that in electricity lies the only means of solving the problem.

As long ago as 1790 Cavendish found that a small amount of nitrogen was combined with water vapor to form nitric acid in the air through which an electric spark had passed, and later investigators found similar traces of this combination in the atmosphere after a thunder shower. The application of these discoveries, however, was made only a few

years ago by Messrs. Bradley and Lovejoy, who began experiments at Niagara. They used an apparatus giving some 400,000 electric sparks per minute in a cylinder through which large quantities of air, with its 80 per cent content of nitrogen, could be forced. The outgoing air contained 2 per cent of fixed nitrogen which could be used in chemical reactions to produce any of the nitrogen compounds desired.

In Norway, where electric power is even cheaper than at Niagara, there are being developed methods in which the air is passed through huge electric arcs with flames nearly a yard in diameter, and, although the direct production of fixed nitrogen from the electric spark or arc is by no means a finished process, it is certainly only a question of a few years before this new activity of electricity will be one of its greatest services. Meanwhile, Dr. Frank of Charlottenburg has discovered a means of causing calcium carbide, familiar as the source of acetylene gas, to combine with nitrogen when reheated in improved forms of electric furnaces, and the compound proves to be an excellent fertilizer. This distinctly electrical product will be used until the direct process is perfected; and so, in one form or another, electricity is fast becoming essential to the maintenance of world life.

The coöperation of electrical and chemical pio-

neers will also be required in improving the efficiency of light-production; and to understand how this is to be brought about it is necessary to consider for a moment just what light is. As the temperature of a body is raised, it begins to send out disturbances in all directions at perfectly definite intervals, new disturbances at shorter and shorter intervals being given off as the body or *radiator* gets hotter and hotter. When the temperature is sufficiently high to cause a part of the disturbances or *waves* to occur 400 millions of millions of times per second, these inconceivably rapid waves striking our eyes make us see the radiator as a dull red. As faster and faster waves are produced the red color becomes lighter, changes to orange, to yellow, and finally to a light white. But, although the temperature is rising, the slower disturbances — the waves which generate heat when they strike any body — are still being sent out at the old rate, and a large part of the work done on the body to raise its temperature to incandescence is thus wasted in heating the air or surrounding bodies. Fortunately, the higher the temperature of the body, the greater the percentage of work which is turned into useful light waves; and if we could get a lamp filament at the temperature of the sun, about one-third of the electrical work done on it would reappear as light.

This means, however, that the filament must withstand a temperature of 5,000° to 6,000° Centigrade (9,000° to 10,800° Fahrenheit), and carbon, the most refractory known substance, melts at 3,700° C.! Even this temperature cannot be reached, except in the arc lamp, for as we found in considering the development of the incandescent lamp (Chapter XI) carbon begins to evaporate at 1,800° C.; and so the limiting temperature for filaments today is just below the melting point of the metal tungsten, 3,200° C. At this temperature only one-fortieth of the electrical energy supplied is converted into useful light! Is there some other substance with higher melting point? and how shall we proceed to find it? All known elements fall into groups according to their various properties, and frequently the discovery of a new element has rewarded the search for that substance which should have the properties required to fill a gap in some otherwise closely related group. Such a gap still exists among the metals between tungsten and osmium (one of the first substances used for metal filaments), and the element to fill this gap will have a higher melting point than any known substance except carbon. The search for this material forms a very real part of present-day pioneering; and, when it is found, light production by incandescent lamps will probably have

reached its greatest efficiency. It is just possible, of course, that chemists may produce compounds of carbon with other elements which will have even higher melting points; but while this may be hoped, it now appears hardly probable.

Are we then to accept a 3 per cent yield as the maximum attainable in the generation of light — three watts out of every 100 converted into the light desired, the remaining ninety-seven going to produce the invisible and useless heat waves? True, this is a considerably better result than can be attained in any of the older forms of illuminants — but it certainly will not satisfy the coming generations whose slogan is to be "efficiency." Even now the way is dimly seen, and considerable advances have been made. In the *flaming arc lamps* dependence is no longer placed on the incandescence of a solid, but the carbons used are first impregnated with certain salts of calcium or other substances, which pass into vapor in the electric arc and there become brilliantly luminous, throwing out light waves far in excess of the amount corresponding to the temperature, so that 10 per cent or even more of the entire electric energy is converted into light.

This suggests that electricity in some way is directly causing the disturbances which we know as light; and, further, that if we could say just what

these disturbances are and just what electricity is efficient light production could be easily accomplished. Here we are back to the question with which we began this book — what is electricity? — and in the answer is to be found not only the solution of the problem of light, but the way to applications of electricity as yet hardly dreamed of. For the last thirty years the nature of electricity has been popularly considered the greatest of mysteries, but even in 1880 it was surely no more mysterious than gravitation, the force which keeps us from flying off the earth as water drops fly from a swiftly revolving wagon wheel; no more unknown than cohesion, the force which holds the particles of this paper or of any other matter together; no more uncanny, indeed, than matter itself. For is not matter so mysterious that even the denial of its existence forms part of certain philosophies and creeds? It is only because electricity is newly come into our fields of knowledge, and so still has clinging to it the atmosphere of the great unknown, that we feel its mystery, a mystery which today is fast passing as a conception of the substance of electricity comes almost within our grasp.

As early as 1873, Clerk Maxwell, the great Scotch mathematical physicist, calculated that an electric charge vibrating back and forth on a conducting body, or indeed, a charged body vibrating

mechanically, would send out disturbances which would travel at the known speed of light, 186,000 miles per second. This could only mean that light waves were produced by rapidly vibrating electric charges; and though the demonstration was purely theoretical it so well accounted for many of the known facts of light and electricity that *the electro-magnetic theory of light*, as it is called, was generally accepted. Since that time Herz and others have discovered ways of producing and controlling vibrating electric charges and of detecting and measuring the speed of the disturbances sent out. This speed has been found experimentally to be that of light, and now these electric waves are the almost commonplace means of transmitting the signals of wireless telegraphy. The disturbances which are easily recognized as electric waves are much slower than those perceived as light, occurring indeed only a few millions of times per second, but the identity of the speed of transmission goes far to verify Maxwell's theory. Now, a vibrating electric charge is equivalent to an alternating electric current; and, as we know, any current is affected by a magnetic field. If the theory is true, therefore, there should be some effect of such a field on the movements of the light-producing charge. This effect was actually discovered with the most refined optical instruments by Zeeman. It consists

in a slight change in the frequency of vibration of the light-giving body, a tiny shift in the color of the light which is sent out. Furthermore, from the measured amount of this change in color, Larmor, Lorentz, and others were able to compute the relation of the amount of charge to the amount of matter in the vibrating body, and thus to find that either the charge was comparatively very great or the body of matter almost infinitely small.

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